Papers presented to the

CONFERENCE ON THE ANCIENT SUN

FOSSIL RECORD IN THE EARTH, MOON AND METEORITES

Boulder, Colorado
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A Lunar and Planetary Institute
Topical Conference

Co-sponsored by
National Center for Atmospheric Research
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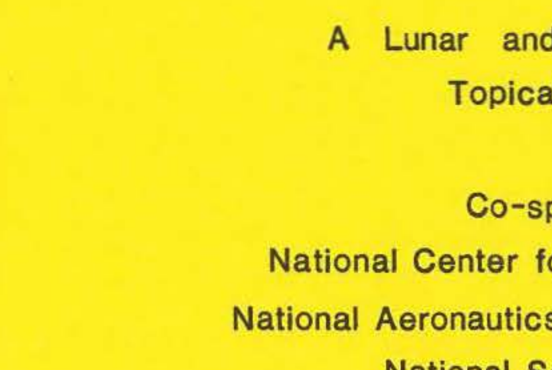

UNIVERSITIES SPACE RESEARCH ASSOCIATION
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PREFACE

This volume contains papers which have been accepted for publication by the Program Committee of the Conference on the Ancient Sun: Fossil Record in the Earth, Moon, and Meteorites. Papers were solicited which address one of the following major topics:

1. The current sun

2. Solar variations on time scales of 100 to 100,000 years

3. Solar variations on time scales of 10^5 to 10^9 years

4. The pre-main sequence sun and the early solar system

The Program Committee consists of J. A. Eddy (*National Center for Atmospheric Research/Smithsonian Astrophysical Observatory*), B. French (*NASA Headquarters*), J. B. Hartung (*State University of New York*), R. E. Lingenfelter (*University of California, Los Angeles*), D. S. McKay (*Johnson Space Center*), R. B. Merrill (*Lunar and Planetary Institute*), G. Newkirk (*National Center for Atmospheric Research*), R. O. Pepin (*University of Minnesota*), R. M. Walker (*Washington University, St. Louis*), N. Weiss (*University of Cambridge, Cambridge, England/Smithsonian Astrophysical Observatory*).

Logistic and administrative support for this conference has provided by P. P. Jones (*Administrative Assistant, Lunar and Planetary Institute*). This abstract volume has been prepared under the supervision of P. C. Robertson (*Technical Editor, Lunar and Planetary Institute*).

Papers are arranged alphabetically by the name of the first author. An index lists papers which were submitted to address each of the four topics. Additional indices by author and subject are included.

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OPPORTUNITIES AND CONSTRAINTS FOR MEASURING TIME SCALES OF SOLAR PROCESSES, J. R. Arnold, University of California, San Diego, Department of Chemistry, B-017, La Jolla, California 92093.

Nuclear processes may be used to study the past emission of high-energy particles from the sun. The methods so far used include measurements of radioactive and stable isotopic products of bombardment and of thermoluminescence (which give evidence on the proton and alpha-particle history) and nuclear tracks (which record nuclei in the iron group and some heavier nuclei). The energy range of particles observed is roughly 10-100 MeV/nucleon. The sun emits such particles during large solar flares.

So far the samples available for studying the fossil record of solar particle (SCR) bombardment have been confined, practically speaking, to documented lunar samples, mainly rocks obtained from the moon by the Apollo astronauts. These are the only materials available whose surfaces have remained exposed to solar protons and heavier nuclei over periods long enough to be of interest. Reedy (1979) has reviewed the results of studies on solar protons since Apollo 11, while Goswami et al. (1979) describe current work and give some references covering the whole area. Briefly, the radionuclides $^{26}Al(t_{1/2} = 7.2 \times 10^5$ years) and $^{53}Mn(3.7 \times 10^6$ years) tell us that the flux and spectrum of SCR particles have been about $J = 70\ p/cm^2$ (>10 MeV) and R_o = 100 MV, both over a 2.0×10^6 year period (Kohl et al., 1978) and over the mean lives of the isotopes. The former period is especially interesting because of its rough correspondence with the Pleistocene era. The values given are somewhat lower than, but comparable to, the flux and spectrum seen experimentally in solar cycles 19 and 20. They might perhaps be close to the mean flux in cycles since about 1800. Data from ^{14}C (5700 years) have supported a higher flux over this period, but Fireman (1978) has done experiments which suggest that the excess ^{14}C is produced in the sun and implanted in lunar rocks at solar wind energies. This is a fascinating but theoretically troubling observation.

The results from rare gas and track data remain difficult to interpret, for various reasons.

The lunar surface rocks are ideal recorders in all respects but one: they are subject to erosion by micrometeoroid impact. The rate of erosion is now reasonably well defined, in the neighborhood of 1 mm/10^6 years (Kohl et al., 1978). However, it does depend on the mechanical properties of the rock, being higher for softer breccias. The correction is serious on a 10^6 year time scale, but not for shorter intervals.

What further data can we hope to obtain which will be of interest to solar physicists? First, it should be possible to resolve the calibration differences which have delayed definitive interpretation of lunar SCR track data (Blanford et al., 1975; Hutcheon et al., 1974; Walker and Yuhas, 1973). These can give us a window into the past, since soil crystals and "rocklets" in our samples have been exposed for various intervals extending back more than 10^9 years, and some breccias are known to have formed, and hence preserved the SCR record, as much as 4×10^9 years ago (Grieve et al., 1975). Spectral shape, and elemental ratios, can be examined. Nuclear track studies in meteoroid impact pit glass can in principle give a ratio of track formation rate (SCR flux) to pit formation rate (meteoroid bombardment flux) (Hartung et al., 1975). The problem with stable (rare gas) products of SCR bombardment is more difficult, since GCR products are present in most samples in much greater abundance. However, there are some promising avenues.

To me the most exciting prospects involve new methods and new materials. The advent of high energy ion counting (Gove, 1978) has increased the list of potentially detectable radionuclides, and can drastically reduce sample size. A group of isotopes in the 10^5 year range (^{41}Ca, 1.0×10^5 years, ^{60}Fe, $3? \times 10^5$ years, and ^{59}Ni, 8×10^4 years), appears especially interesting. On the moon, ^{41}Ca is made by a variety of proton-induced processes, while the other two are produced chiefly by α-particle bombardment of iron (Wahlen et al., 1972). In samples of meteoritic composition, proton bombardment of Ni is important.

Measurement of SCR fluxes in some meteorites may prove possible, but ablation has removed the record in nearly all cases. One possibility now coming into view is the use of deep-sea spherules (Brownlee, 1978). Some or even most of these may be fused micrometeoroids, whose dimensions in space were of the same order as the present range of diameters (0.1-1 mm). According to calculations, SCR-produced radionuclides should dominate in this size range. Moreover, these objects should sample a volume of space in the solar system much larger than the earth's orbital zone. Finally, they are available from core layers of defined terrestrial age, and hence can sample a range of periods on the order, perhaps, of 10^5-10^6 years, going back to 10^7 years or even beyond. Experiments in this field are just beginning (Nishiizumi and Brownlee, 1979).

The sun's activity should also affect the GCR flux. At one time we expected large effects of this kind, but recent probe data have made us much less certain of the true situation. There may be a revival of interest in this field when we have probe data from well out of the ecliptic plane. At least some deep sea spherules, of cometary origin, must sample regions far outside the sun's magnetic influence.

Lastly, I will describe an experiment which may not ever be possible, but which is conceptually illuminating. Suppose that two non-gaseous radionuclides of similar half-life (say $\sim$300 years to fix our ideas) were produced and brought to the earth's surface in different ways: nuclide A as an SCR product in micrometeoroids, and nuclide B as an SCR product in the earth's atmosphere. Then both would fall out and be incorporated in Antarctic or Greenland ice cores, where yearly layers can be distinguished. Nuclide A would give a record of the running mean, averaged over one mean life, of SCR production in the sampled region of the solar system. It would be insensitive to such phenomena as the Maunder minimum. By contrast, nuclide B would give a record of production year by year, since the atmospheric holdup time at high latitudes is negligible. The interpretations would, as always, depend on our knowledge of some other variables, but still the results could be dramatic.

In this field we are engaged in a process partly cyclic and partly progressive. Each advance in our understanding of past SCR and GCR fluxes gives us a tool to understand the history of other processes, such as lunar gardening or Antarctic ice flow. What we learn about these can be applied back to improving our knowledge of temporal variations of solar particle activity. We know these variations exist on short time scales -- we can see them. On a longer scale our fragmentary evidence suggests approximate constancy.

It seems probable that further studies will uncover variations on longer time scales as well, and that these will give us an important window on the sun's history.

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SUNSPOT CYCLE SIMULATION USING RANDOM NOISE J. A. Barnes and H. H. Sargent III, U. S. Dept. of Commerce, National Bureau of Standards, Boulder, CO 80303

Since the discovery of the cyclic behavior of sunspots by Schwabe in 1843, many authors have referred to the sunspot record as an example of naturally occurring periodic behavior. Yule (1) characterized the sunspot numbers as a "disturbed harmonic function" which he likened to the motion of a pendulum which boys are pelting with peas. Time series analysis texts (2,3,4) and statistical works (5,6) commonly cite the sunspot number series as a function which is more or less periodic. The noisy, but nearly periodic, character of the sunspot record has led the authors to a very simple model of solar activity which mimics the observed sunspot numbers to a surprising degree. The observed annual mean sunspot numbers (7) and simulated annual mean sunspot numbers (produced using methods described in this paper) are shown in Fig. 1.

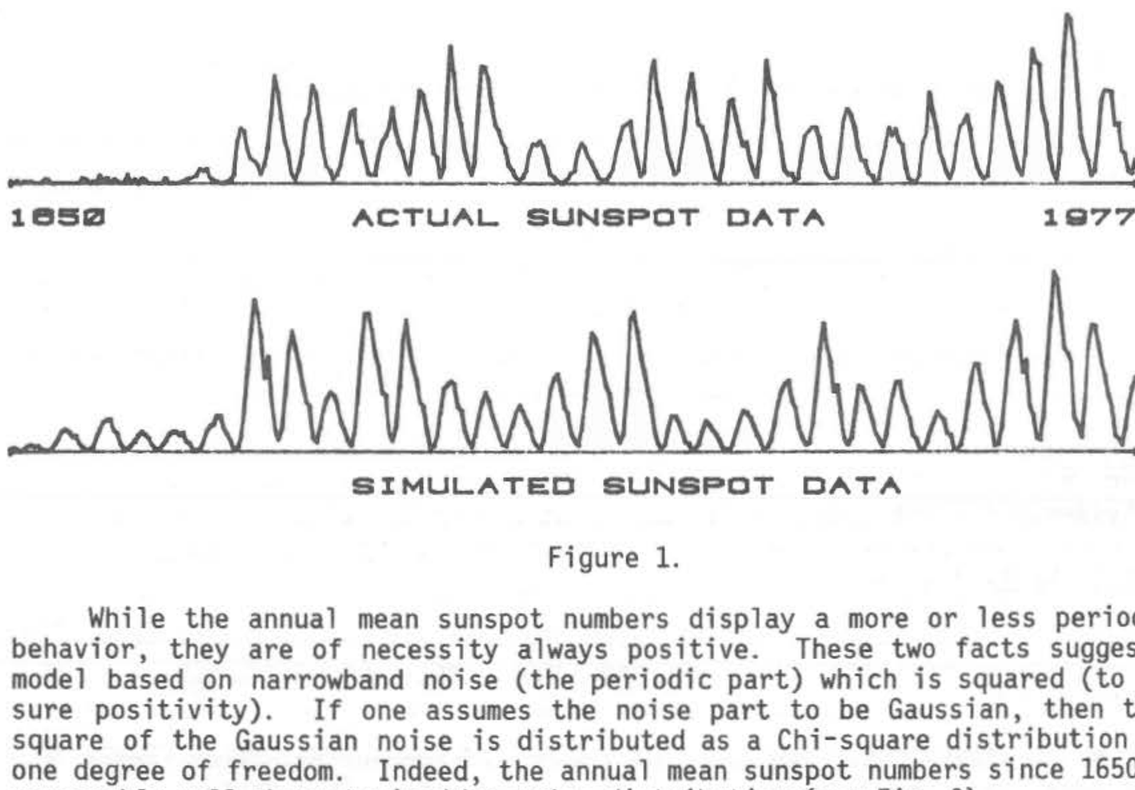

Figure 1.

While the annual mean sunspot numbers display a more or less periodic behavior, they are of necessity always positive. These two facts suggest a model based on narrowband noise (the periodic part) which is squared (to insure positivity). If one assumes the noise part to be Gaussian, then the square of the Gaussian noise is distributed as a Chi-square distribution for one degree of freedom. Indeed, the annual mean sunspot numbers since 1650 are reasonably well characterized by such a distribution (see Fig. 2).

In order to model the actual annual mean sunspot numbers more closely, two cosmetic features have been added: (a) a broadband ("white") noise, and (b) a rise/fall correction to simulate the rapid rise and slower fall observed in the larger sunspot cycles. This completes the model which was used to produce the simulated data plotted in Fig. 1. Of course, the rise/ fall correction slightly distorts the distribution function from a perfect Chi-square distribution and, in fact, the simulated distribution is closer to the actually observed distribution than is the Chi-square distribution as shown in Fig. 2.

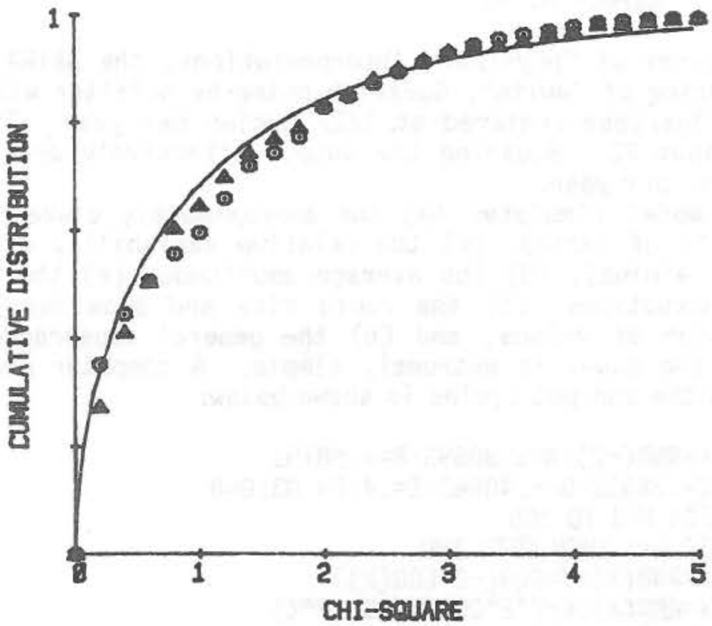

Figure 2. Cumulative distributions for observed annual mean sunspot numbers (circles) and simulated annual mean sunspot numbers (triangles) divided by their means for 328 years. The solid curve is the Chi-square distribution for one degree of freedom.

For computer simulation, the narrowband noise plus the broadband noise is generated by an Auto Regressive, Integrated, Moving Average (ARIMA) model (8). The output of the ARIMA model is squared and a rise/fall correction applied. The simulation equations are as follows:

$Z_n = a_n = 0$ for $n < 1$ (initial conditions)

$Z_n = \phi_1 Z_{n-1} + \phi_2 Z_{n-2} + a_n - \theta_1 a_{n-1} - \theta_2 a_{n-2}$ (ARIMA model)

where* $\phi_1 = 1.90693$ $\theta_1 = 0.78512$

$\phi_2 = -0.98751$ $\theta_2 = -0.40662$

Z_n are the output of the ARIMA model, and

a_n are random, normal deviates with zero mean and standard deviation

$\sigma_a = 0.4$.

$X_n = Z_n{}^2$ (square of Z_n)

$Y_n = X_n + \alpha\,(X_{n-1} - X_{n-2})^2$ (rise/fall correction)

where $\alpha = 0.03$, and the Y_n simulate annual mean sunspot numbers.

---

*Since the coefficients ϕ_1, ϕ_2, θ_1, and θ_2 interact with each other, the number of significant digits given here is very large relative to the confi-cence intervals of the "physical" parameters. Dropping digits can materially alter the model beyond what one might normally expect, because roots of the "operator" equation are changed significantly. This is often an annoying feature of digital filters and does not imply exactness in the overall model.

SUNSPOT CYCLE SIMULATION...

Barnes J. A.

In terms of "physical" interpretations, the ARIMA model corresponds to the filtering of "white", Gaussian noise by a filter with a bandwidth of about 0.002 cycles/year centered at 1/22 cycles per year. This corresponds to a "Q" of about 23. Squaring the output effectively doubles the frequency to 1/11 cycles per year.

The model simulates (a) the approximately eleven-year period, (b) the variability of period, (c) the relative variability of amplitude (including "Maunder" minima), (d) the average amplitude, (e) the short term (year-to-year) fluctuations, (f) the rapid rise and slow decay, (g) the observed distribution of values, and (h) the general appearance of sunspot cycles. Further, the model is extremely simple. A computer program in Basic which simulates the sunspot cycles is shown below:

```
100 X=RND(-2):A=1.90693:B=-.98751
110 C=.78512:D=-.40662:E=.4:F=.03:G=0
130 FOR N=1 TO 300
140 IF G=1 THEN GOTO 180
150 X=RND(X):Y=SQR(-2*LOG(X))
160 X=RND(X):K=Y*E*COS(6.28318*X)
170 G=1:GOTO 190
180 G=0:K=Y*E*SIN(6.28318*X)
190 H=A*I+B*J+K-C*L-D*M
200 M=L:L=K:S=I*I-J*J
210 T=H*H+F*S*S
220 PRINT T
230 J=I:I=H
240 NEXT N
250 STOP
```

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RADIATION DAMAGE IN MICRON-SIZED LUNAR DUST GRAINS AND THE PROPERTIES OF THE ANCIENT SOLAR WIND. J. Borg, J. Chaumont, Y. Langevin and M. Maurette, Laboratoire René Bernas, 91406 Campus-Orsay, France.

I. EARLIER RESULTS : THE VELOCITY OF THE ANCIENT SOLAR WIND.

We previously reported (1,2) on a new method intended to detect possible change in the velocity of the ancient solar wind (SW) over a very long time scale of 3.5 billion years, never explored before. This method relies on the high voltage electron microscope observation of micron-sized feldspar grains, randomly extracted from the lunar regolith. We start in measuring the thickness, Δ, of the ultra-thin amorphous coatings of solar wind radiation damaged material (SW-AC) observed on a great number ($\gtrsim$ 500) of individual grains. We thus obtain the thickness distribution, $dN/d\Delta$, of the SW-AC, that shows very specific features, such as a marked peak occuring at $\sim$350 Å and a large spread of Δ values ranging from 100 Å up to 1000 Å (figure 1). The next step is to conduct solar wind simulation experiments, by irradiating grains fixed on electron microscope substrates ("fixed-grain" irradiation geometry) in the beam of an ion implanter.

By combining the results of such simulation experiments with data concerning the elemental composition of the solar wind, we deduced that α-particles are mainly responsible for the formation of the SW-AC. As a result of solar wind ion sputtering these coatings reach an equilibrium value, in about 2,000 yr of SW-exposure, which is proportional to $k.\langle v_\alpha \rangle^n$, where $\langle v_\alpha \rangle$ is the speed of the α-particles as averaged over the same period, and $n \lesssim 2$ for $v_\alpha \lesssim 400$ km.s^{-1}. The last but most difficult step is to interpret the thickness distribution of the fossil coatings reported in figure 1, by taking into consideration the exposure history of lunar dust grains in the ancient solar wind.

To decipher this history we had to develop a Monte-Carlo statistical code, that do in fact account for the complex dynamical evolution of the lunar regolith, as triggered by the meteoritic rainfall. Our computations, when performed for 1 µm-grains, indicate that the "average" grain is exposed only once for about 5,000 yr in the SW. Furthermore, for a random sampling of grains the epochs of such 5,000 yr-exposures should be randomly spread over the typical lifetime of the corresponding regolith material, which is about 3.5 billion years for lunar maria. With such a SW-exposure history, the $dN/d\Delta$ distribution should reflect the frequency distribution of periods of about 5,000 yr in duration, during which the solar wind had a velocity, $\langle v_\alpha \rangle$, easily inferred from the experimental scaling law, $\Delta \sim k.v_\alpha^n$. Thus, the marked peak in the distribution corresponds to a velocity of $\sim$ 400 km.s^{-1} similar to the present day value. But there is also an anomalously high frequency of periods of low SW-velocity at the Moon, as well as a few periods of much higher SW-velocity. We show in the next section how these conclusions have to be modified in the light of our most recent unpublished work, that somewhat complicates the interpretation of the $dN/d\Delta$ distribution while still increasing the potential of the method.

II. RECENT RESULTS : THE VELOCITY AND THE He/H ABUNDANCE RATIO OF THE ANCIENT SOLAR WIND.

II.1. Simulation experiments with "rotating-grains".

The fixed-grains (Fg) irradiation geometry does not well simulate lunar processes, that are expected to frequently change the orientation of lunar grains during their SW-exposure. Consequently, we injected 1 µm-grains into a cylindrical wheel that rotates around the ion beam axis, in thus triggering a continuous turn over of the grains during their irradiation (rotating-grain geometry). For a given ion, the thickness of the amorphous coating, Δ_{Rg}, is now much larger than the value, Δ_{Fg}, measured for the fixed-grain geometry. In particular the Δ_{Rg}/Δ_{Fg} ratio, which is about 2 for α-particles, clearly increases for heavier ions. Thus the scaling law, $\Delta_{Fg}(v_\alpha)$, used in our previous interpretation of the $dN/d\Delta$ distribution, has to be changed, and the peak in the distribution reported in fig. 1 should be shifted to a velocity of $\sim$ 250 km.s^{-1} much smaller than that of the present day solar wind.

II.2. Recent simulation experiments with the fixed-grain geometry.

For various raisons the high proton fluences required for comparing the ion implantation effects of protons and α-particles could not be achieved either with the new Rg-geometry or with our previous Fg-geometry. However, as a result of improvments in the ion implanter design this comparison can now be made with the Fg-geometry. We thus reconfirmed our previous striking finding that α-particles are about 30 times more efficient than protons for producing an amorphous coating. But we also measured for the first time the Δ_{Fg} values of protons, in noting that for a given velocity these values are about two times smaller than that previously inferred just by extrapolating to protons the constant Δ_{Fg} value measured for ions ranging from deuterons up to xenon ions.

The combination of these two recent results further complicates the interpretation of the anomalously high frequency of thin SW-AC inprinted on the $dN/d\Delta$ distribution, and previously attributed to α-particle velocities smaller than the present day values. Indeed this striking feature of the distribution could as well reflect periods of marked decreases in the He/H abundance ratio, below a critical value of $\sim$ 2 %, during which the protons contribution dominates the formation of the SW-AC, in thus loading lunar dust grains with coatings much tinner than these expected for α-particles with the same velocity.

But in addition the Δ_{Rg} value expected for the protons, and which has to be used for the interpretation of the $dN/d\Delta$ distribution (relevant to lunar dust grains that rotate during their SW-exposure) should be about 2 times larger than the experimental Δ_{Fg}-values (see section III). This implies that the peak now attributed to the protons in the $dN/d\Delta$ distribution is still shifted to a velocity smaller than the contemporary value. Consequently these new results seem to reinforce our previous conclusion of an atypical contemporary solar wind, while further extending the potential of the method.

III. DISCUSSION AND CONCLUSIONS

Under the friendly and very stimulating guidance of P. Sigmund we have successfully interpreted some of the results of our simulation experiments, that look very odd at first glance, in term of the theory of collision cascades in solids (3). In particular the Δ_{Rg}/Δ_{Fg} ratios are similar to the theoretical ratios between the so-called "longitudinal and transverse spread" of the damage distribution. The same interpretation also well account for the constant Δ_{Fg} values noted at a given velocity for Xe, A, Ne, He and D ions, as well as for the smaller value measured for the protons. Consequently, in the interpretation of the $dN/d\Delta$ distribution presented in section II we have used for the proton the theoretical estimate of the Δ_{Rg}/Δ_{Fg} ratio, for evaluating Δ_{Rg} from the measurement of Δ_{Fg}.

From our Monte-Carlo computations we also proposed an interesting lunar "skin" sampling technique, intended to date the epoch of the 5,000 yr exposure of micron-sized lunar dust grains in the ancient solar wind, as well as that of the solar cosmic rays exposure of grains with a size of 1 mm, that we use as track detectors for measuring several characteristic of the ancient solar cosmic rays at the same epoch. In this technique both the 1 µm and the 1 mm-grains are extracted from the top ∿ 5 mm-thick layers of the constituent strata of lunar core tubes (4).

We thus believe that we are in a good position for tracing back the past activity of the Sun, as we can possibly look now at two distinct types of solar "radiations" and/or two different characteristics of the ancient solar wind. However we have still to address ourselves to the following questions, before making any further claim for an <u>atypical contemporary Sun</u> :

1. Are the predictions of our Monte-Carlo computation so far compatible with the corresponding experimental observations ?
2. Can we sort out the SW-AC due to protons and/or α-particles in the dN/dΔ distribution ?
3. Are the velocity and the He/H ratio of the solar wind affected by the complex natural processes active during the "maturation" of lunar dust grains ?
4. Do planetary and galactic processes (drastic changes in the configuration of the Earth's magnetosphere ; collision of the solar system with interstellar clouds ; etc ...) leave prints on the dN/dΔ distribution, that further complicate its interpretation ?

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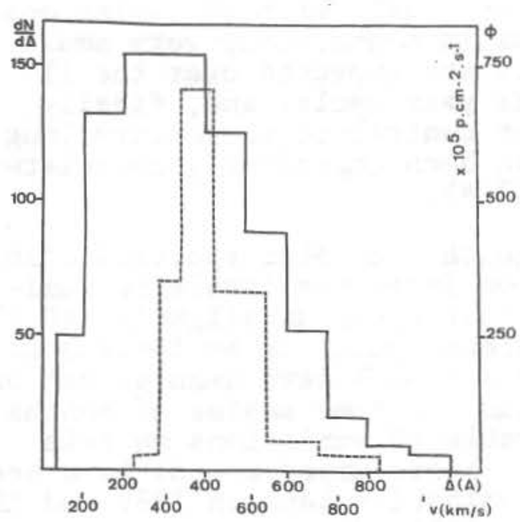

<u>Figure 1</u> : The solid line histogram gives the experimental dN/dΔ distribution measured for a great number (≳ 500) of micron-sized feldspar grains, randomly extracted from the top to bottom section of the Apollo 15 core tube. The velocity scale, v(Δ), was deduced from the thickness of the amorphous coatings by relying on the results of the "fixed-grains" simulation experiments, that clearly overestimate the velocity corresponding to a given Δ value. Consequently the peak in the distribution should be now shifted to a smaller velocity of ∿250 km. s^{-1}. The dashed line histogram represents the velocity distribution of the contemporary solar wind, as measured on the lunar surface with an active detector during the Apollo 12 mission (5). The measurements reported on the solid line and dashed line histograms correspond to time intervals of 5,000 yr and ∿ 30 minutes, respectively.

"THE INFLUENCE OF SOLAR UV VARIATIONS ON CLIMATE"
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Good empirical correlations have been obtained between variations in solar activity and climate on time scales on the order of a week (1) and a century (2,3). Also, such solar terrestrial relationships have been suspected for periods equal to once and twice the 11 year sunspot cycle (4,5). However, the physical mechanisms that are responsible for such connections remain unknown, despite a number of plausible suggestions (2,6,7,8).

Observations of the sun from satellite and rocket platforms have provided good evidence that solar radiation varies noticeably in the ultraviolet portion of the spectrum over a solar rotation period of 27 days (1,2). There is also less conclusive evidence for such variations on the time scale of the 11 year sunspot cycle (1,2). In this paper, we investigate the possible effects of these UV variations on atmospheric ozone content and climate for time scales encompassing the 27 day solar rotation period, the sunspot period, twice this period (solar magnetic period), and much longer times. We conclude that solar UV variations on time scales of months can noticeably perturb temperatures and therefore perhaps the dynamics in the upper stratosphere and mesosphere, but they result in only very minor changes in the energy balance below the tropopause; that the above cited estimates of UV variation over the 11 year solar cycle are inconsistent with measured changes in global ozone abundances; that, with UV variations being bounded by long term trends in ozone, only very small variations in surface temperature are expected over the 11 year solar cycle, and over the 22 year cycle; and, finally, that solar spectral changes might contribute to century long variations in climate, which have been empirically correlated with changes in solar activity (3,4).

In order to clearly distinguish the solar spectral change mechanism for climate modification from ones involving luminosity changes, we alter the visible spectrum slightly (<0.3%) so that the integrated solar radiant output is an invariant. We note that very severe upper bounds (.03%) have been placed on the variation of the solar constant on time scales of months (5), despite the occurrence of measurable UV variations on this same time scale (1,2). Somewhat larger upper bounds have been set on the change in the solar luminosity between 1969 and 1976 (.15%) (6) and from 1923 to 1952 (.16%) (7).

There have been other studies of the relation between solar UV variations and atmospheric ozone content and stratospheric temperatures (8,9,10). Our efforts differ from these by estimating the impact of such variations on tropospheric temperatures, by holding the total luminosity constant, and by examining the dependence of the ozone variations on the forcing period.

"THE INFLUENCE OF SOLAR UV VARIATIONS ON CLIMATE"

Borucki, W.J., J.P. Pollack, O.B. Toon

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LUNAR NITROGEN: EVIDENCE FOR SECULAR CHANGE IN THE SOLAR WIND

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The abundance and isotopic composition of nitrogen in lunar soils lead to two conclusions: (1) the current solar wind intensity is too low by a factor of about five to account for the observed concentrations, and (2) the $^{15}N/^{14}N$ ratio of solar wind nitrogen has apparently increased by at least 30% over lunar history.

Nitrogen, along with hydrogen, carbon and the noble gases, is very strongly depleted in indigenous lunar materials relative to solar, or even terrestrial, abundances. Lunar igneous rocks usually contain less than 1ppm N (Becker and Clayton, 1975; Becker et al., 1976). Lunar soils, on the other hand, contain substantial abundances of these very volatile elements due to accretion of solar wind and perhaps of meteoritic materials. Lunar soils typically contain 50-100 ppm N (Becker and Clayton, 1975, 1977; Becker et al., 1976; Kerridge et al, 1975; Petrowski et al., 1974). If the present-day solar wind flux at 1 a.u. is taken as 1×10^{-8} proton/cm^{2}sec., and if the solar wind has the solar elemental abundance ratio N/H=1.2×10^{-4}, then a lunar regolith of average thickness of 5 meters would acquire 10ppm N over 4×10^9 years. The observed concentrations, which are at least five times as great, imply either (1) a much higher flux in the past, (2) a thinner regolith (unlikely), (3) enrichment of the solar wind in N relative to H (unlikely). An excess of similar magnitude can be calculated for solar-wind Xe in lunar soils. Thus, nitrogen and xenon, the most effectively trapped of all of the volatile solar wind species on the lunar surface, indicate a substantially greater intensity of solar wind in the past.

The isotopic ratio $^{15}N/^{14}N$ of the implanted nitrogen varies by over 30% in different lunar samples. Those which received their surface exposure to the solar wind in the remote past (2-4 billion years ago) have ratios about 20% lower than the terrestrial atmosphere (Thiemens and Clayton, 1979). The solar wind implanted recently has an isotope ratio about 10% higher than the atmospheric value (Becker et al., 1976). There is not yet firm evidence that the variations reflect a monotonic secular increase in the implanted $^{15}N/^{14}N$ ratio, but such a trend is compatible with the data. The difficulty in determining the nature of the time variation in $^{15}N/^{14}N$ ratio arises from the absence of an independent technique for establishing when a particular sample was on the lunar surface. Core samples with known stratigraphic relations are of some help, but each one usually covers a relatively small time interval.

Processes are known which lead to alteration of isotopic abundances of various elements on the lunar surface. For oxygen, silicon, sulfur and potassium, loss of a fraction of these volatile elements from the moon has left a residue enriched in the heavier isotopes (Clayton et al., 1974). Nuclear spallation reactions with the galactic cosmic rays may also change the isotopic abundances (Becker and Clayton, 1977). Both types of process would tend to produce enhanced ^{15}N abundances in ancient soils, whereas, in fact, the opposite trend is observed. Thus we conclude that the secular variation in implanted $^{15}N/^{14}N$ ratio represents a change of composition in the source of the nitrogen, not a change which occurred subsequently on the moon.

It is difficult to prove that nitrogen implanted into lunar soils some three billion years ago was all of solar origin, rather than perhaps meteoritic or cometary. However, nothing in the chemical or isotopic compositions of the ancient irradiated samples suggests the presence of an unusual amount of meteoritic material. Furthermore, no known meteorites have $^{15}N/^{14}N$ ratios remotely similar to the values found in ancient lunar soils (Kung and Clayton, 1978).

We are therefore left with the conclusion that the most likely cause for the isotopic variations in lunar nitrogen is a variation in the source of the solar wind itself. The nature of solar processes which might have led to such large effects in isotopic composition have been discussed by Kerridge et al. (1977). No satisfactory explanation has been found. Obviously, interpretation of the nitrogen data would be aided if correlated isotopic effects were found in other elements. The most obvious elements for consideration are hydrogen, carbon and the noble gases. The light noble gases are not very satisfactory since they are poorly retained. Carbon might be expected to exhibit sympathetic isotopic variations, but of a factor of 10 lower amplitude due to the isotopic abundances of ^{13}C and ^{15}N, and of their likely precursors in spallation reactions. However, carbon apparently undergoes much larger isotopic variations due to lunar chemical processes, so that any variations in its source are masked (DesMarais et al., 1975; Kerridge and Kaplan, 1978). It may nevertheless be possible to investigate the specific lunar samples in which the ancient implanted nitrogen component is particularly well preserved so as to recognize small isotopic effects in other elements.

Besides the difficulty of understanding the apparent 30% variation of $^{15}N/^{14}N$ in the solar wind, we also note that neither the isotopic composition of the present solar wind, nor of the inferred ancient solar wind, is similar to the compositions of terrestrial nitrogen or meteoritic nitrogen. Thus the relationship between solar and planetary nitrogen in the early solar system is still obscure.

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THE PRESENT AND PAST NEUTRINO LUMINOSITY OF THE SUN, Bruce C. Cleveland, Raymond Davis Jr., J. Keith Rowley, Brookhaven National Lab.* and W. Hampel and T. Kirsten, Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

The neutrino radiation from the sun can give direct information on the basic nuclear fusion processes that provide the solar energy. Measurements have been performed over the last seven years with the Brookhaven solar neutrino detector that depends upon the neutrino capture reaction $^{37}Cl(\nu,e^-)^{37}Ar$. A signal above known background effects has been observed that corresponds to a total neutrino capture rate of 2.2 ± 0.4 SNU (SNU $\equiv$ solar neutrino unit = 10^{-36} captures per second per ^{37}Cl atom). Current theoretical models of the sun forecasts neutrino capture rates in ^{37}Cl of 5 to 8 SNU. It is of great interest to know whether the lack of agreement between the measurements and theoretical expectation could possibly be explained by a secular variation in the rate of the fusion process. With this possibility in mind radiochemical neutrino detection techniques have been proposed that could in principle record the neutrino flux in the past. These methods necessitate measuring long-lived isotopes produced by neutrino capture in natural minerals. This method of recording neutrino fluxes in the past has serious background problems resulting from cosmic rays and alpha radiation from uranium and thorium contamination. The limitations of this method of recording past solar neutrino luminosities will be evaluated quantitatively. An analysis will be given of expected background processes for two experiments that have been proposed recently; one uses the neutrino capture process $^{205}(Tl(\nu,e^-)^{205}Pb^* \rightarrow {}^{205}Pb$ ($t_{1/2} = 1.4 \times 10^7$ y) (1), the other uses the process $^{81}Br(\nu,e^-)^{81}Kr^* \rightarrow {}^{81}Kr$ ($t_{1/2} = 2.1 \times 10^5$ y) (2). These and other possible methods of recording the past solar neutrino luminosity will be discussed in relation to variations expected from theoretical solar models.

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CONTINENTAL GLACIATION ON EARTH THROUGH GEOLOGIC TIME: ARE THE CAUSES TERRESTRIAL OR EXTRATERRESTRIAL? J. C. Crowell, Department of Geological Sciences, University of California, Santa Barbara, CA 93106

The record of climate on Earth is contained within sedimentary rocks and extends back in time beyond 3 BY but with diminishing clarity and time resolution as strata become older. Erosional and depositional processes of the mobile crust tend to destroy or cover up this record. Nonetheless, documentation is preserved and such strata have long been under study by geologists but usually with little emphasis on climatic interpretation and still less on the basic causes of climate change. Modern techniques of stratal analysis, interpreted with global tectonic concepts in mind, however, are allowing better founded inferences concerning climate change during this long span. It is therefore appropriate here to review briefly aspects of this record in order to evaluate possible terrestrial causes on the one hand and extraterrestrial causes on the other. Perhaps data from outside of the Earth show changes in climate-influencing factors, such as changes in solar flux, that correspond in time with climate changes on Earth. The data from beyond Earth will help in sorting out these influences, and this knowledge, in turn, will aid in arriving at a theory of climate change. And this bears significantly on the continuing welfare of mankind.

Continental glaciation represents an extreme climatic variation on Earth that has come and gone irregularly. Ice sheets, especially if they reach the sea, leave a record in the form of subaqueous tillite, dropstones in thin-bedded sequences, striated and faceted stones, and, where there is consolidated rock beneath them on land, striated pavements. This glacial evidence on a regional scale can usually be distinguished from similar appearing rocks formed in other ways, such as by down-slope sliding of unconsolidated debris. The distribution and dating utilizing geologic, paleontologic, and geochronologic methods of such beds discloses that there have been five distinct ice ages during the past 2.3 BY that are well established.

Earth at present is witnessing the Late Cenozoic Ice Age, but an interglacial stage within it. This ice age started in the Miocene Epoch between 10 and 15 MY ago. Previously there was a long interval of about 225 MY without continental ice sheets, back to within the Permian Period about 240 MY ago. The Late Paleozoic Ice Age lasted for 90 MY, on back in time to 330 MY ago (1,2). Near the transition between the Ordovician and Silurian periods, between 445 and 425 MY ago, there was a sharp and short Ice Age that lasted for only 20 MY. The record of Late Precambrian glaciation is widespread and appears to have lasted at places into the Cambrian Period. Although dating is poor in general for these Precambrian - Cambrian deposits, glaciation occurred on all continents, and at some places twice, during the 230 MY interval between 750 and 520 MY ago. No broad glaciation has been recognized for the immense interval of 1450 MY back to 2200 MY although local controversial deposits have been reported in Greenland, Finnmark, and China with ages between 950 and 850 MY (3). The next older ice age (the Huronian, including the Gowganda) is dated between 2335 and 2200 MY and is quite well established. Reports of older glacial beds, perhaps as old as 2800 MY are questionable (3).

The terrestrial causes of ice ages seem rooted in the effect of continental arrangements on the air-ocean system (1,2). With clustering of continents in high latitudes, there is a polar or subpolar site on which the ice can accumulate. If the continents are arranged so that they force the flow of warm tropical and subtropical water to high latitudes, a ready source for evaporation may lie upflow from suitable glacial sites. Broad expanses of

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continents in middle and high latitudes may encourage snow cover in winter over much larger than average areas and so increase the albedo that in turn may lower the average Earth temperature. Volcanism, sea-level changes, cloudiness, storm tracks, location of mountains and uplands, are among additional factors. As worldwide data come in, reconstructions of paleogeography during the ice ages is improving so that in the decades ahead we may be able to evaluate these influences with enhanced confidence. Scientists may conclude, however, that more than terrestrial influences are involved. If so, we must evaluate the timings of extraterrestrial events to see if they match the timings of refrigerations on Earth in a plausible way. (1) Crowell J. C. and Frakes L. A. (1970) Amer. Jour. Science, v. 268, p. 193-224. (2) Crowell J. C. (1979) Amer. Jour. Science, v. 278, p. 1345-1372. (3) Harland W. B. and Herod K. N. (1975) p. 189-216 in Wright A. E. and Moseley F. (eds.) Ice Ages: Ancient and Modern, Seel House Press, Liverpool, 320 p.

SOLAR FLARE AND GALACTIC COSMIC RAY TRACKS IN LUNAR SAMPLES AND METEORITES. Ghislaine Crozaz, Earth and Planetary Sciences Department and McDonnell Center for the Space Sciences, Washington University, St. Louis, Mo. 63130

The present discussion will concentrate on one of the effects of the bombardment of lunar samples and meteorites by heavy ions of both galactic cosmic rays and solar flares, namely the formation of nuclear particle tracks. A complementary review by Reedy will treat the information derived from the study of radionuclides produced by interaction of both the lunar surface and the meteorites with galactic and solar flare protons. Additional reviews by Pepin, Maurette and Clayton of solar wind effects in these materials are also relevant to the general subject of the interaction of energetic nuclear particles with extraterrestrial materials. An overview of the nature of the fossil evidence is given by Walker. Only selected references are included in this abstract. Additional references pertinent to the subject will be found in the forthcoming proceedings paper.

The solid state damage resulting from the penetration of ionizing particles from the solar and galactic cosmic rays in an insulating material can be sufficiently intense to disrupt the atomic structure and produce latent tracks which can be chemically etched to produce holes (tracks) that are observable by optical microscopy (if their density is very high electron microscopy is required). For a general review of the phenomenon and its many applications, see (1). Tracks in silicate minerals are only produced by heavy ($Z \geq 20$) particles at the end of their range (10-20μm for an iron nucleus) where their ionization rate is maximum. Most tracks in meteorites and lunar materials are caused by ionizing particles of the iron group ($20 \leq Z \leq 28$, called VH for very heavy ions). Longer tracks due to heavier nuclei (VVH) are much rarer because of the steep drop in elemental abundances beyond iron. Tracks produced by solar flares dominate in the upper 1 mm of materials directly exposed to the sun whereas galactic cosmic ray particles penetrate to depths of many cms. In addition, the track density falls off very rapidly in the outer mm and more slowly thereafter.

Meteorites, during their passage through the earth's atmosphere, lose the record of the low energy solar radiation which was preserved near their original surface. However, certain meteorites (gas-rich and certain carbonaceous chondrites) contain interior grains which were once directly exposed to the sun, prior to the formation of the meteorite. This exposure may have occurred early in the history of the solar system thus extending the time scale for study of solar flare effects to more than 4 b.y.

Thus, in principle, meteorites and lunar samples offer a unique opportunity to study solar activity during the last billions of years. Deciphering this record is unfortunately far from simple. To mention only a few problems: lunar rocks usually experience a complex irradiation history during which their irradiation geometry varies. Their bombardment by micrometeorites also causes a continuous erosion of their surface which modifies the track density depth profile. In addition, different soil grains from a given location experience unique histories which are the result of repeated exposures at the surface. Trying to determine when a specific grain was last exposed is usually an impossible task. In spite of these serious complications and limitations, a number of important conclusions about solar flares in the past have been derived from the study of nuclear particle tracks in extraterrestrial materials. They are summarized below:

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1) the solar flare activity has persisted at least for the last 4×10^9 yrs. Gas-rich meteorites and certain carbonaceous chondrites contain up to 20% of solar flare track rich olivines which in some cases are also covered with craters due to hypervelocity impacts of micrometeorites. Both effects were acquired by the grains prior to their incorporation in the meteorites. This compaction event probably occurred over 4.2 b.y. ago (2). Detailed observations of these meteorites also revealed the rare presence of impact glass, agglutinates, chondrules, and foreign clasts which further attest to the regolith origin of these meteorites which have much in common with lunar breccias (3). Differences in the intensities of these effects (systematically lower in meteorites) have been attributed to differences in gardening rates on the respective parent bodies and in distances from the sun. Housen et al. (4) and Dran et al. (5) have recently attempted to model asteroidal regoliths and explain gas-rich meteorites. At this point in time, there is substantial disagreement between the two models. No attempt has been made to interpret the results in terms of a temporal change of the solar flare activity as there is no independent method to determine the length of exposure of meteorite grains to solar rays.

Although it will probably never be possible to detect an eventual solar flare intensity change using meteorites, these objects have provided evidence that:

2) the energy spectrum of solar flare particles has probably not changed much during the last 4 b.y. Information on the properties of contemporary heavy solar flare particles (see review by Zinner) was provided by the analysis of a glass filter from the Surveyor III spacecraft which was exposed on the lunar surface for almost three years. The energy spectrum can be represented by a relation of the form $dN/dE = AE^{-3}$. Such a depth dependence was also observed in lunar crystals recently exposed in vugs or locations where erosion was negligible during the irradiation interval. The solar flare depth dependence in most lunar rocks is flatter than expected from the Surveyor spectrum because of erosional processes. However, when the effect of erosion is taken into account, the observed track density depth dependences are consistent with the Surveyor profile, i.e. do not indicate any significant change in the energy spectrum during the last few m.y. In addition, the steepest profiles of solar flare track densities in meteoritic breccias are also similar to the Surveyor glass profile, suggesting again that the energy distribution in solar flares has not changed with time (6). It is worth noting though that it cannot be ascertained whether the shallower track gradients frequently observed are all due to the known effects of erosion or shielding (7) or rather to genuine variations of the solar flare energy distribution. What is most significant is that no profile steeper than the Surveyor profile has been observed.

3) heavy particles are enriched relative to lighter particles at energies <10 MeV/nucleon. The original observation by Price et al. (8) in the Surveyor filter was later confirmed using plastic/glass and electronic detector systems. It is one of the most important results of lunar solar flare studies and it was completely unexpected. The reasons for the progressive enrichments of heavy particles at low energies are not yet understood but it is now established by measurements of fossil tracks in lunar soils (9) and meteorites (10) that this behavior is a characteristic of ancient as well as modern flares.

4) the VVH/VH ratio in solar flares. This is an area where disagreement still persists. The VVH/VH ratio is usually determined by measuring track length distributions although Dartyge et al. (11) have started to study

partially annealed tracks by small angle x-ray scattering techniques. Proper calibration of track registration properties of different crystals has been a continuing problem. Price et al. (12) and Kratschmer and Gentner (13) performed calibration experiments. However, the track length distribution is a function of etching time and can be modified by thermal and shock effects; all these factors make it extremely difficult to construct a reliable charge vs. track length calibration. It is not surprising, therefore, that results do not always agree (for a discussion, see 11). This is still a problem area but, potentially, the record is there to be analyzed.

5) No evidence for a higher solar activity during the early history of the moon has yet been accepted. Poupeau et al. (14) found in the Luna 16 soils that feldspars identified (on the basis of their etching rate) as anorthosites likely of highland origin (and hence old) had much higher track densities than feldspars characteristic of mare basalts (and hence younger). They ascribed these striking differences in track densities to enhanced solar activity at the beginning of the solar system. Crozaz et al. (15) assigned individual feldspar crystals to particular lithologies on the basis of microprobe analyses and were unable to reproduce these results in other mature soils.

However it has to be realized that it is unlikely that we may be able to recognize a higher earlier activity of the sun even if it occurred; the best samples for this type of study are the lunar cores because, at depth, they contain grains which may have been irradiated at the surface billions of years ago. Determining the depositional history of lunar cores is not an easy task and ambiguities exist (see for ex. 15). The fundamental problem is that most soils are complex mixtures of grains each of which has had an individual irradiation history. Untangling the combined effects of possible solar activity variation and complex irradiation histories of unknown lengths can be highly speculative!

In addition, studies of nuclear particle tracks produced by galactic cosmic rays in extraterrestrial materials have also led to important results which are only briefly mentioned here. Fleischer et al. (17) discovered and first measured the abundances of VVH particles in galactic cosmic rays, using meteorites. The galactic cosmic ray track production in extraterrestrial material is well established. There is no evidence for a change of either galactic cosmic ray intensity, average composition or spectrum during the last 50 m.y. (1) Fleischer R. L. et al. (1975) Nuclear Tracks in Solids. U. Cal. Press. (2) Macdougall J. D. and Kothari B. K. (1976) Earth Planet. Sci. Lett. 33, 36-44. (3) Rajan R. S. (1974) Geochim. Cosmochim. Acta 38, 777-788. (4) Housen K. R. et al. (1979) Icarus, in press. (5) Dran J. C. et al. (1979) Lunar and Planetary Science X, 309-311. (6) Price P. B. et al. (1973) Proc. Lunar Sci. Conf. 4th, p. 2347-2361. (7) Poupeau G. et al. (1975) Proc. Lunar Sci. Conf. 6th, p. 3433-3448. (8) Price P. B. et al. (1971) Phys. Rev. Lett. 26, 916-919. (9) Bhandari N. et al. (1973) Astrophys. J. 185, 975-983. (10) Goswami J. N. and Macdougall (1977) Meteoritics 12, 242-243. (11) Dartyge E. et al. (1978) Proc. Lunar Sci. Conf. 9th, p. 2375-2398. (12) Price P. B. et al. (1973) Earth Planet. Sci. Lett. 19, 377-395. (13) Krätschmer W. and Gentner W. (1976) Proc. Lunar Sci. Conf. 7th, p. 501-511. (14) Poupeau G. et al. (1973) Geochim. Cosmochim. Acta 37, 2005-2016. (15) Crozaz G. et al. (1974) Proc. Lunar Sci. Conf. 5th, p. 2591-2596. (16) Crozaz G. and Ross L. H., Jr. (1979) Proc. Lunar Planet. Sci. Conf. 10th, in press. (17) Fleischer R. L. et al. (1967) J. Geophys. Res. 12, 355-366.

The Altitude of the Aurora Determined by the Source of Particles Emitted from the Sun

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ABSTRACT

The altitude of the aurora is shown to be inversely proportional to an index of the recurrence probability of magnetic storms. The recurrence phenomenon is related to energetic particles emitted from "coronal hole" regions on the sun, while the more sporadic solar flare sources associated with a larger flux of lower energy particles produce aurora at higher altitudes in the atmosphere. Thus, the altitude, and therefore the color and form of the aurora observed in the earth's atmosphere reflects directly the predominant type of particle source on the sun.

Historical Observations of the Aurora as a Measure of the Relative Effect of Solar Activity and the Geomagnetic Field on ΔC^{14} in the Atmosphere.

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ABSTRACT

A change in atmospheric C^{14} is inversely related to solar activity or the strength of the geomagnetic field or both. These two effects on atmospheric C^{14} can be separated by relying on the color of the aurora to determine solar activity and the position of the aurora to determine the strength of the magnetic field. Historical records of aurora indicate for example, that the "grand maximum" of solar activity, seen in ΔC^{14} records to occur between 1120 and 1280 AD, probably began earlier during the period when the Norse Prose Edda were composed (700 - 1100 AD). There is, however, no direct reference to auroral occurrence in Norse literature before 1500 AD even though there were widespread reports from Europe and elsewhere. This and other evidence indicates that the geomagnetic field during that time was quite different from its present condition. Several important changes in the historical record of atmospheric C^{14} are shown probably to be associated with changes in the geomagnetic field on a time scale of tens of years.

LIMITS OF HISTORICAL EVIDENCE OF SOLAR VARIABILITY.

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Direct observations of the solar surface and accounts of proxy indicators such as auroral occurrence allow us to reconstruct an historical record of solar behavior that reaches about 2000 years into the past (1). The utility of the record falls off sharply with time, and particularly so if one is interested in the recovery of solar variations of known terrestrial importance. For example, reliable, quantitative measurements of the total integrated sunlight (radiative flux, or "solar constant") exist for little more than the last 10 years and a continuous record of solar flares covers less than the last 50 years.

Measurements of various forms of solar surface activity constitute the longest direct record of solar behavior but this, too, drops abruptly in quality before the introduction of the telescope in 1610. Before that time it is possible, however, to reconstruct a broad survey of solar behavior that can be compared with less-direct natural indicators of solar activity such as radiocarbon abundances from dated tree-ring samples (2,3,4). When this is done, good agreement is found between gross features of the historical and the natural records.

Our longest record of solar variability is the history of sunspot occurrence. The sunspot number as presently defined was introduced in 1848; reconstructions from historical data extend the record, less reliably to 1610. Under favorable conditions sunspots can be detected with the unaided eye and a thin, though continuous record exists as far back as the first century, B.C., when the earliest account of a sunspot is found in Chinese records. Recent compilations of pre-telescopic sunspot accounts based on dynastic records from China, Japan and Korea (5,6,7) have discussed the utility of the record, the limitations imposed by possible suppression of data, and the question of determining whether or not evidence exists for an 11-year sunspot cycle in the early, pre-telescopic accounts.

The nature of solar surface rotation can be reconstructed from careful analyses of the early telescopic sunspot observations; recent studies of these data (8,9,10) have suggested significant secular changes in the character of photospheric rotation at the time of the Maunder Minimum that could indicate changes in the solar convective region and variability of the solar dynamo.

Direct observations of the solar diameter have been made with transit telescopes since AD 1750, when a regular program was initiated at the Royal Greenwich Observatory. Recent analysis of these data suggests a possible secular shrinking of the Sun that could be of fundamental importance in solar energy generation (11).

Occurrence of the terrestrial aurora borealis and australis are related to conditions on the solar surface and may be interpreted within certain limits as an indirect indicator of solar activity in the past. Records extend to about 1000 years B.C., although very few auroral reports are found before the time of the Renaissance. Although often used as a simple, proxy indicator

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of sunspot number (12), auroral occurrence is a more complex index of conditions on the Sun. Recent understanding of the role of coronal holes on the Sun and of aurorae that result from high speed streams of solar wind that originate in these open field regions have helped to understand why significant numbers of aurorae are seen that are out of phase with conventional indices of solar activity.

Direct observations of the solar corona at eclipse afford another potential record of past solar activity. Although literary references to eclipses extend far back in recorded history, there are as yet no known descriptions of the solar electron corona before 1715. (1) Eddy, J.A. (1977) in The Solar Output and Its Variation, O.R. White, Editor, Colo. Assoc. Univ. Press, p. 51. (2) Eddy, J.A. (1976) Science 192, p. 1189. (3) Eddy, J.A. (1977) Climatic Change 1, p. 173. (4) Eddy, J.A. (1978) in The New Solar Physics, J. A. Eddy, Editor, Westview Press, p. 11. (5) Clark, D.H. and Stephenson, F.R. (1978) Quart. J. Royal Astron. Soc. 19, p. 387. (6) Stephenson, F.R. and Clark, D.H. (1978) Applications of Early Astronomical Records, Adam Hilger, Ltd., p. 87. (7) Wittmann, A. (1978) Astronomy and Astrophysics 66, p. 93. (8) Eddy, J.A., Gilman, P.A. and Trotter, D.E. (1976) Solar Physics, 46, p. 3. (9) Eddy, J.A., Gilman, P.A. and Trotter, D.E. (1977) Science 198, p. 824. (10) Herr, R.B. (1978) Science 202. (11) Eddy, J.A. and Boornazian, A.A. (1979) Bull. Amer. Astron. Soc. 11, p. 437. (12) Schove, D.J. (1955) Journal of Geophys. Res. 60, p. 127.

ROTATIONAL HISTORY OF THE SUN: SPIN-DOWN OF THE INTERIOR BY CIRCULATION CURRENTS AND FLUID INSTABILITIES. A. S. Endal, Dept. of Physics and Astronomy, Louisiana State Univ., Baton Rouge, LA 70803 and S. Sofia, Astronomy Program, Univ. of Maryland, College Park, MD 20742.

Solar-type stars arrive on the main sequence while rotating much faster than the surface layers of the present Sun. Two well-established observational results strongly support this conclusion:

(a) If main-sequence stars rotate as rigid bodies, the mean angular momentum per unit mass j(M) as a function of total mass M obeys the smooth relationship $j(M) \propto M^{0.57}$ for $M > 1.5M_\odot$ (1). A sharp break occurs at $1.5M_\odot$, with less massive stars rotating much more slowly. The rotation rate of the present Sun is a factor of 60 below the j(M) relationship, if the interior rotates at the same rate as the surface.

(b) Among solar-type stars, the youngest stars are the fastest rotators. The rotation rates for the Pleiades stars (age $\sim 3 \times 10^7$ yrs.) are only a factor of 3 below the j(M) relationship (2). Similar results have been obtained for other young clusters. Further, the pre-main-sequence T Tauri stars have rotation rates which place them very close to the j(M) relationship, even though most of them have masses below $1.5M_\odot$ (1).

The break in j(M) at $1.5M_\odot$ can be explained by angular momentum losses due to a magnetically-coupled stellar (solar) wind (3,4). Substantial angular momentum loss will only occur if the star has a deep convective envelope which can generate the required magnetic field. Above $1.5M_\odot$, the convective envelopes are too shallow to generate such fields (5). Rotational braking by solar winds during the main-sequence life time is also consistent with the rapid rotation of young main sequence stars and the T Tauri stars. The observations indicate a surface spin-down time scale of the order of 10^8 yrs. An important question is: how will this braking of the surface layers affect the rotation of the interior?

Angular momentum can be transferred from the solar interior to the surface by a number of mechanisms, as discussed, for example, by Endal and Sofia (6). Convection and shear and baroclinic instabilities can transport angular momentum in dynamical time scales. However, convection is confined to a small portion of the total mass and the fluid instabilities will only operate if there is substantial differential rotation (in the radial direction). Circulation currents driven by thermal inbalance (Eddington circulation), the Goldreich-Schubert instability, and a thermal form of the shear instability will transport angular momentum on thermal time scales (10^7 to 10^9 yrs.). Eddington circulation, in particular, will persist even for rigid-body rotation so these thermal mechanisms are likely to play an important role in the spin-down of the solar interior. However, these mechanisms can be quenched by radial gradients in chemical composition (μ-barriers) generated by nuclear burning, if the μ-barriers are generated more rapidly than circulation currents can mix the interior. Since the nuclear and mixing time scales and the surface spin-down time scale (see above) are all comparable, numerical simulations are necessary to determine the final outcome.

The simulations involve simultaneous solution of the time-dependent stellar structure equations (including rotational effects) and equations describing angular momentum transport. The angular momentum distribution is continually adjusted to satisfy the constraints of dynamical stability. Angular momentum and mass transport by thermal mechanisms are handled by time-dependent diffusion equations with the diffusion coefficients specified by an

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eddy viscosity model of the circulation currents. These techniques have proved highly successful in modelling the observed rotational velocities of massive stars evolving off the main sequence (7).

The solar simulations start with a pre-main-sequence model rotating rigidly at the rate implied by the j(M) relationship described above. As the model evolves, the surface convection zone is spun down on a time scale consistent with recent solar wind calculations (8). The evolution of the interior structure and angular momentum distribution is then followed and the results checked against observable parameters (i.e., luminosity, radius, and oblateness). The oblateness has proved a very important parameter since the observed value (9) places tight constraints on the interior rotation of the present Sun. (1) Kraft R. P. (1970) in Spectroscopic Astrophysics, ed. G. H. Herbig (U. of California Press, Berkeley), p. 385-422. (2) Anderson C. M. et al. (1966) Astrophys. J., vol. 143, p. 299-305. (3) Brandt J. (1966) Astrophys. J., vol. 144, p. 1221-1222. (4) Weber E. and Davis L. (1967) Astrophys. J., vol. 148, p. 217-227. (5) Durney B. R. and Latour J. (1978) Geophys. Astrophys. Fluid Dyn., vol. 9, p. 185-255. (6) Endal A. S. and Sofia S. (1978) Astrophys. J., vol. 220, p. 279-290. (7) Endal A. S. and Sofia S. (1979) Astrophys. J., in press. (8) Belcher J. W. and MacGregor K. B. (1976) Astrophys. J., vol. 210, p. 498-507. (9) Hill H. A. and Stebbins R. T. (1975) Astrophys. J., vol. 200, p. 471-483.

ISOTOPIC COMPOSITION OF HYDROGEN AND OXYGEN OF CELLULOSE IN TREE RINGS AND ITS CLIMATIC SIGNIFICANCE S. Epstein, Div. Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

It has been known for many years that the isotopic composition of both hydrogen and oxygen of the earth's surface water (meteoric water) is related in a qualitative way to the climatic temperature of the area where the water is found. It has been shown that the isotopic composition of unexchangeable hydrogen in cellulose extracted from a large variety of plants reflects the isotopic composition of water available to them during their growth periods. Consequently, the isotopic composition of the hydrogen in unexchangeable hydrogen in cellulose reflects qualitatively the climate of the location in which the plant grew. The isotope analyses of hydrogen extracted from cellulose in tree rings from a single tree should permit the measurement of climatic changes over a period of time covered by the age of the tree. These isotopic changes may also include in part the variation in relative humidity of the environment in which the tree grew. By analyzing isotopically tree rings in trees like the bristlecone pine it may be possible to obtain a record of climatic changes over long periods of time. It is also possible to analyze these climatic changes for the presence of climatic cycles.

We have analyzed a thousand year record of hydrogen in cellulose of bristlecone pine from the White Mountain areas in California. Two types of analyses have been made. Ten year intervals of tree rings were analyzed for the past 1000 years of growth. In addition, 5 year intervals of tree rings were made for the part of the tree which grew in the last 500 years of growth. Both sets of data were Fourier analyzed and a strong 22 year cycle was observed in both series.

The Fourier analysis of the five year interval data did not show an 11 year cycle. If an 11 year cycle existed in the data it should have been apparent in the Fourier analysis of this data. In addition the data for the five year interval sampling for different 200 year growth periods were Fourier analysed. These analyses showed that the last 200 year growth period had the strongest 22 year cycle and the 200 year period between 1570-1770 showed little of the 22 year cycle. Several additional trees about 150 years old from various climatic environments were analyzed isotopically using five year interval tree ring samples. A cedar tree located in Sequoia National Park showed an unusually excellent 22 year cycle whereas pine trees from Oregon and from Scotland lacked the 22 year cycle in their isotopic data.

The relationship between the 22 year cycles in the isotope data and the solar cycle is probably real. Nevertheless, caution is recommended because not all trees record these cycles and it is important to find out what are the factors that determine whether a tree records or does not record cycles. In this manner it may be possible to ascertain whether the sunspot activity does in some way affect the isotopic composition of meteoric water and thus the isotopic composition in hydrogen and cellulose. The establishment of the correlation between the hydrogen isotopic composition of cellulose and solar activity will provide an extremely valuable tool for studying the history of the sunspot activity as far back as fossil cellulose remains preserved. Cellulose has been found in plant material which grew thousands and even millions of years ago.

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GALACTIC COSMIC RAY VARIATIONS DURING THE PERIOD 1967 TO 1978; COSMOGENIC RADIONUCLIDE PRODUCTION IN METEORITES. J. C. Evans, L. A. Rancitelli, J. H. Reeves, Battelle Northwest and D. D. Bogard., Johnson Space Center, Houston, Texas 77058

The galactic cosmic ray flux produces a record of its energy and intensity in the shielded lunar samples and meteorites over time periods directly proportional to the half life of the resulting cosmic radionuclides. These radioisotope records have been used in attempts to better understand the variation of the galactic cosmic ray spectrum over a solar cycle. Fireman (1) attempted to show the relationship of the ^{22}Na variation with time during a solar cycle. Several workers (2-4) have tried to correlate solar cycle variations with ^{37}Ar/^{39}Ar ratios. Most recently, other workers, most notably Bhattacharya et al. (5) and Bhandari et al. (6) have attempted to relate cosmic isotope production to spatial and temporal variations and flux. The shortcoming of most of these studies has been that they were directed towards a few meteorites with rather limited isotope production systematics.

As an integral part of our lunar studies of the cosmic ray history as revealed by selected samples, we have been conducting a systematic study of cosmic radionuclides in meteorite falls. To date 43 fragments from 24 meteorite falls occurring between 1967 and 1978 have been studied for a comprehensive suite of gamma ray emitting cosmic radionuclides. These radionuclides include ^{7}Be, ^{22}Na, ^{26}Al, ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{56}Co, ^{57}Co, ^{58}Co, and ^{60}Co. They were measured by non-destructive techniques of gamma ray analysis (7) in a systematic fashion which lends a high degree of internal consistency and accuracy to the body of data. Samples of those same meteorites were also analyzed for rare gases in order to verify that the expose ages are long enough to saturate ^{26}Al. The results of this study indicate that during the period 1967 to 1978 the ^{22}Na content of meteorites corrected for shielding and target chemistry using the observed to calculated ^{26}Al content (Fuse and Anders) (8) is a smoothly varying function with a 40% variation, has a broad minimum during the period 1970-1971, and slowly reaches a maximum in 1977. The ^{54}Mn content (313 days) in meteorites again corrected for shielding effects, during this period varies smoothly by a factor of about 2, at the minimum in 1971 and at a maximum in 1977. ^{46}Sc (83.8 days) also smoothly varies with time by a factor of 2, with maximums and minimums closely paralleling those of ^{22}Na and ^{54}Mn. In order to demonstrate that the observed variation is caused by cosmic ray modulation it is necessary to correlate this data with solar activity parameters. Figure 1A shows sun spot number plotted on an inverse scale or as reference. Neutron monitor data from the Deep River neutron monitor is plotted in Figure 1B. A production calculation was carried out for expected activities of ^{22}Na, ^{54}Mn, and ^{46}Sc at the time of fall. Differential production rates were scaled by monthly average Deep River neutron monitor count rates and weighted by a saturation and decay factor. Absolute rates were normalized to the observed average values at solar minimum. The results of the production calculations are shown in Figures 1C, 1D, and 1E. Those production curves were then regression fit to the experimental data which is shown in Figure 2A, 2B, and 2C. Reasonably good coherence is obtained for the ^{46}Sc and ^{22}Na data indicating a link to solar modulation. The fit is less convincing for ^{54}Mn perhaps due to poorer quality data. It is concluded that the solar modulation effect on cosmic ray production rates in meteorites is much larger than expected. Instantaneous rates may differ by up to a factor of 3 between solar maximum and solar minimum. Rare gas exposure ages based on ^{22}Na-^{22}Ne may be uncertain by $\mp$20%, due to this effect. Forman et al. (9) have suggested that a very large solar modulation effect during the Maunder and Sporer minimum may have produced observable effects in the form of ^{39}Ar excesses in meteorites

GALACTIC COSMIC RAY VARIATIONS

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and excesses in the ^{14}C record. This work suggests that the required large variation may indeed be possible.

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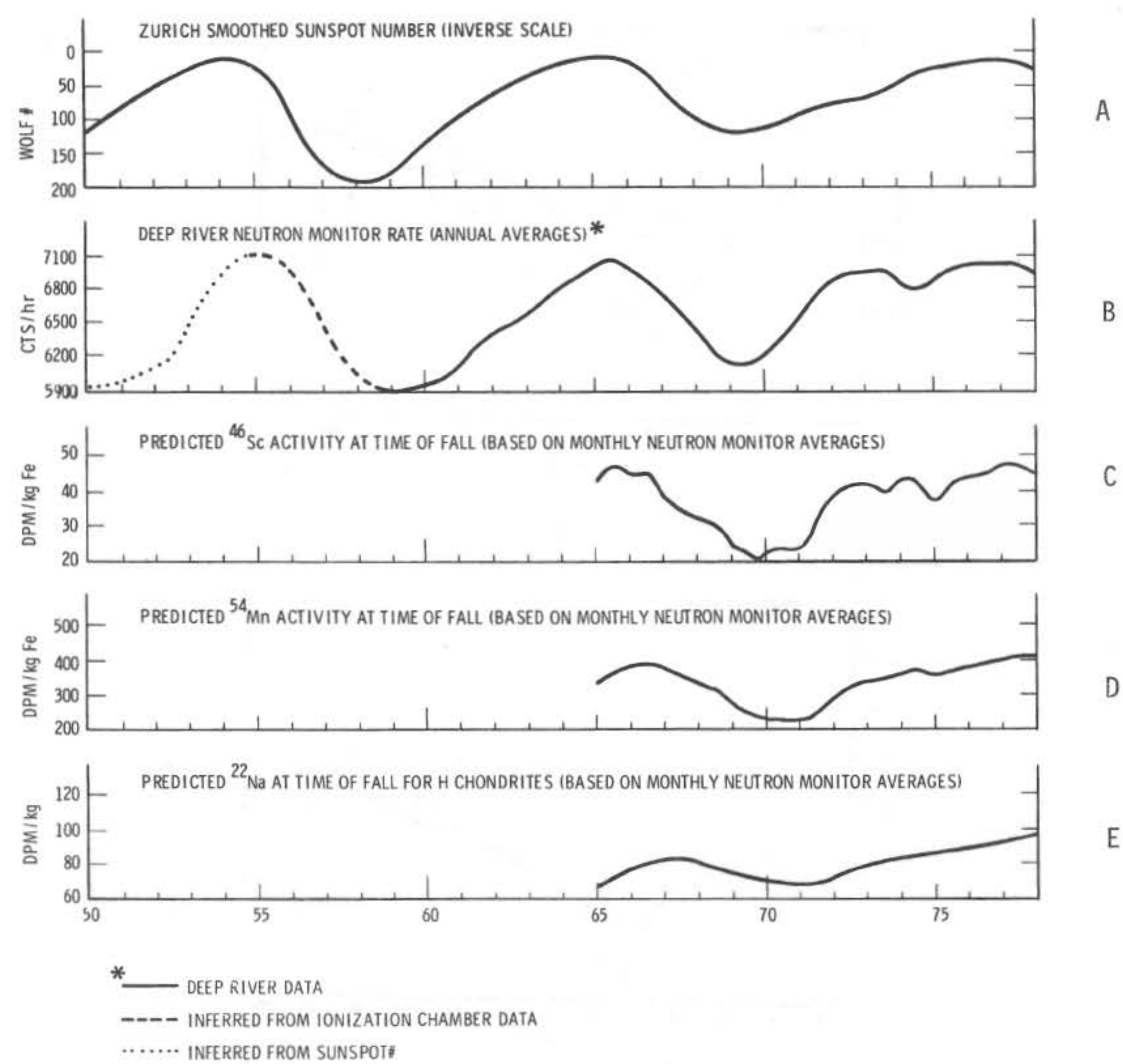
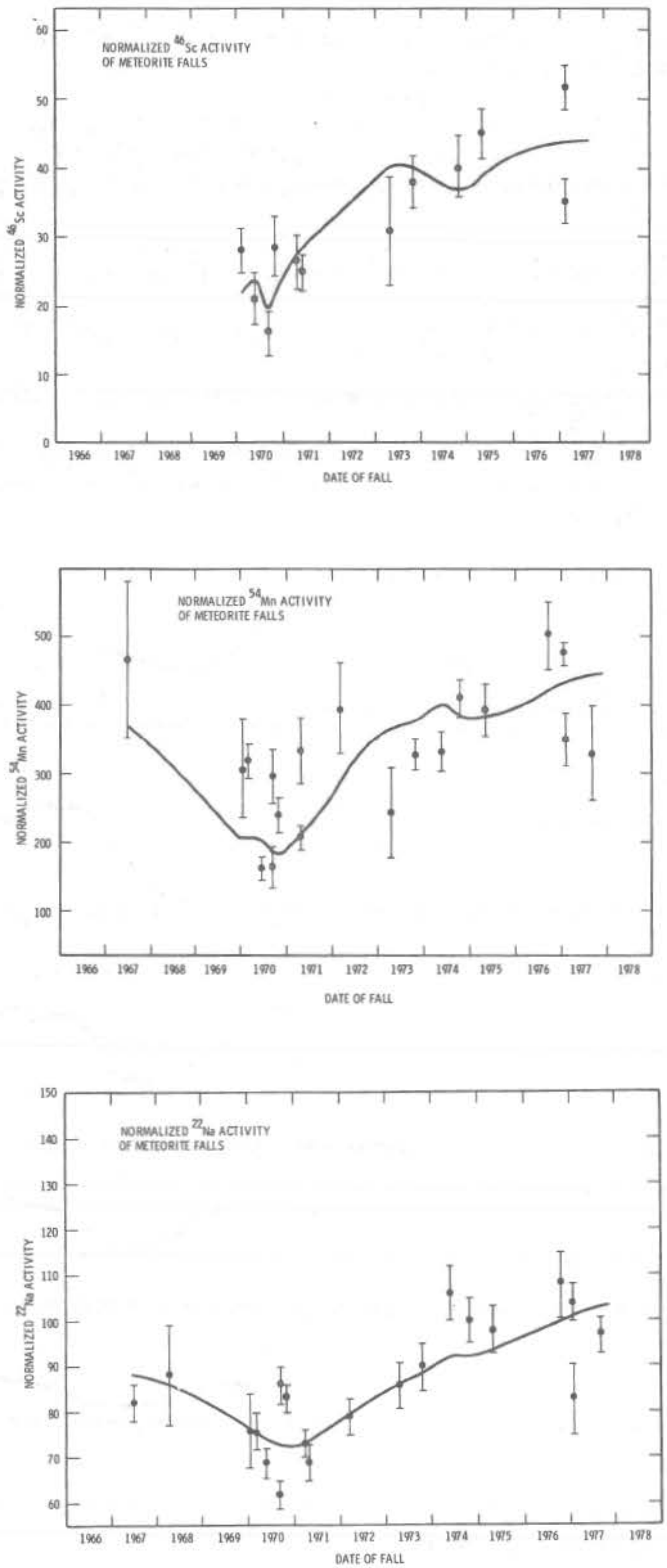


Figure 1

GALACTIC COSMIC RAY VARIATIONS

Evans, J.C., Rancitelli, L.A., Reeves, J.H. and Bogard, D.D.



A

B

C

Figure 2

CARBON-14 VARIATIONS IN TERRESTRIAL AND MARINE RESERVOIRS DURING THE LAST 11 MILLENNIA

A. W. Fairhall, University of Washington, Seattle, WA 98195 and A. I. C. Yang, U.S. Geological Survey, Arvada, CO 80002

Saanich Inlet is a narrow fjord on the Southeast shore of Vancouver Island, British Columbia. The deep waters of this basin are anoxic during most of the year so that the accumulated sediments are undisturbed by burrowing organisms. Intense summer blooms of diatoms, followed by deposits of terrigenous sediment laid down during the winter and spring have resulted in a 38m accumulation of varved sediment during the last 11 millenia. This sediment was cored by rotary drilling resulting in 11 overlapping 6.5m x 15cm diameter cores from 5m depth in the sediment to the bottom of the deposit.

After splitting the cores in two, lengthwise, the varved structure was revealed by X-ray photography of thin strips of sediment taken from the center of each core. Counting the varves allows one to estimate the age of the sediment at a given depth. Furthermore, since about 8,700 years ago the cores occasionally contain fragments of terrigenous organic matter: twigs, chips of wood, cones, and bits of charcoal which can be dated by C-14 to obtain an independent check on the varve chronology.

Aliquots of the sediment were taken for C-14 dating, giving a C-14 chronology as a function of varve chronology. The latter is presumed to represent the absolute age of the sediment. The results are in good agreement with similar measurements on bristle cone pine: beginning about 2,000 years ago the C-14 age is increasingly too young, becoming 800 years too young at about 6,000 (calendar) years ago. Beyond 6,000 years ago the deviation between the age given by C-14 dating and the absolute age decreases until at about 8,500 years ago the C-14 age is the same as the varve (calendar) age. The terrigenous material also shows a maximum deviation between C-14 and varve (calendar) age at ca. 6,000 years ago and the discrepancy decreases as one goes back in time beyond 6,000 years ago. However, from a modest extrapolation of the data the time at which the C-14 age of terrigenous material was equal to its true (calendar) age is estimated to have been 11,000 years ago. The discrepancy between this result and that for the varved sediment is attributed to changes in the mixing rate of the deep ocean associated with the end of the last ice age.

To explain the origin of the C-14 variations a simple model was constructed in which the C-14 production rate Q(t) is assumed to be modulated by the earth's dipole magnetic field M(t): $Q(t) \propto M(t)^{-1/2}$. Over the past 9 millenia M has been observed to fluctuate sinusoidally with a period of 8,000 years:

$$M(t) = M_o\ (1.0 + 0.5 \sin 0.25\pi t)$$

where time is measured in millenia backwards from the present and Mo is the present value of the earth's magnetic field. Using a simple 2-box

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model for the carbon reseroirs, one being the deep ocean the other being the terrestial biosphere, atmosphere and mixed layer of the sea, and a 1,000 year residence time for carbon in the deep ocean reservoir, the model assumed a steady-state situation 48 millenia ago which was the same as today's. This is long enough ago that whatever the true state of affairs was at that time it will have been "forgotten" today. The modulation of the earth's dipole field was then switched on and the C-14 content of the two reservoirs was calculated as a function of time. The results for the two reservoirs are in good agreement with the observations from about 6,000 years ago to the present. However, beyond 6,000 years ago the observed C-14 content of the atmosphere - terrestrial biosphere is higher than the model predicts. If the rate of formation of bottom water were to slow down, and this seems likely to occur during times of rapid melting of high-latitude ice sheets, decreased ocean mixing would result in an accumulation of C-14 in the atmosphere - terrestrial carbon reservoir. This may explain the discrepancy between the predictions of the model and the observed higher C-14 content of terrigenous material in the interval between 6,000 and 11,000 years ago.

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SOLAR-PRODUCED AND IMPLANTED RADIONUCLIDES IN LUNAR SAMPLES. E.L. Fireman, Smithsonian Astrophysical Observatory, Cambridge, Mass. 02138

Radionuclides with different half-lives in lunar samples provide information on the history of energetic solar-flare particles and about implanted radionuclide abundances. The depth dependences of seven radionuclides have been measured. These are (in order of increasing half-life) ^{37}Ar, ^{22}Na, ^{3}H, ^{39}Ar, ^{14}C, ^{26}Al, and ^{53}Mn; the half-lives range from 35 days to 3.7×10^6 yr. The implanted concentration can not be separated from the nuclear interaction concentration unless other investigations besides depth studies are made. We discuss radionuclides on the basis of nuclear interactions unless implantations are indicated by the other studies.

For deep samples (≥ 10 g/cm^2 depth), all lunar radionuclides are in good accord with a constant flux of galactic cosmic-rays averaged over three half-lives. For shallow samples (< 10 g/cm^2), there is more radioactivity than can be accounted for by galactic cosmic-rays. We treat only ^{37}Ar, ^{39}Ar, and ^{14}C here.

^{37}Ar has a 35 day half-life; solar flare inferrences made from lunar ^{37}Ar data can be checked with space-probe data. Because of the high Ca abundance in lunar material and the high $^{40}Ca(n,\alpha)^{37}Ar$ and $^{40}Ca(p,\alpha)^{37}K$ cross sections, essentially all ^{37}Ar is produced from ^{40}Ca. ^{37}K decays to ^{37}Ar with a 1.2-sec half-life. ^{37}Ar measurements have been done for Apollo 12, 14, 15, 16, and 17 sample selected from different depths (1, 2, 3, 4). Significant flares occured before the Apollo 12, 14, 16, and 17 missions but not before the Apollo 15 mission.

Measurements from the Smithsonian Astrophysical Observatory (1, 3) and from Brookhaven National Laboratory (2, 4) are shown in Figs. 1 and 2. For large depths, the $^{37}Ar/Ca$ ratios for different missions are identical. For shallow depths, the $^{37}Ar/Ca$ ratios differ markedly with the samples from the Apollo 15 mission having the lowest $^{37}Ar/Ca$ ratios.

Table 1 summarizes pertinent data for the surface samples, 0 to ~ 2 g/cm^2. The third column gives the $^{37}Ar/Ca$ ratio for the mission surface sample minus the $^{37}Ar/Ca$ ratio of the Apollo 15 surface sample. The $\Delta^{37}Ar/Ca$ is corrected to the time of the solar flare. The last column gives the integrated solar-flare (> 60 MeV) proton fluxes from space-probe data. The correspondence between the $[\Delta^{37}Ar/Ca]_{cor.}$ ratios and the solar-flare (> 60 MeV) proton fluxes is good except for the bottom row. The $[\Delta^{37}Ar/Ca]$ ratios correspond to the (> 15 MeV) proton fluxes for all four flares if a $1/E^{1.9}$ differential energy spectrum is used for the Aug. 4, 1972 and a $1/E^{3.5}$ spectra for the others. This comparison demonstrates the importance of the flare hardness in flux estimates. One can not estimate the solar-flare fluxes averaged over the past $\sim 10^3$ yr from the ^{39}Ar data or averaged over the past $\sim 10^4$ yr from the ^{14}C data unless an assumption is made about the hardness of ancient flares. We shall assume the hardnesses of solar flares averaged over 10^3 and 10^4 yr are both given by a $1/E^3$ differential energy spectrum.

The Aug. 4, 1972, solar flare did not contribute significantly to the ^{39}Ar activities in Apollo 17 samples. The ^{39}Ar activities in the Apollo 17 samples (3, 4) are not higher than those from earlier missions (1, 2). The Apollo 11 samples had the highest ^{39}Ar activities which is explained by its chemical compositions. The ^{39}Ar activities are essentially constant at shallow depths and decrease at large depths (3, 4). By use of cross-section measurements and Reedy and Arnolds calculations (5), Steinbrunn and Fireman (6) concluded that the solar flare protons during the past 1000 yr must have had a higher flux than averaged over the past 3 solar-cycles or that solar flare He particle reactions on Ca were very significant during the 10^3 yr period. Begemann et al. (7) measured the ^{39}Ar activities in two grain-size fractions of soil 12001, $< 44\ \mu$ and $> 75\ \mu$; they found that the larger grains had the activity expected from rock measurements but that the smaller grains had three times less ^{39}Ar activity. Since the chemical compositions of the fractions are very similar, ^{39}Ar was lost from the smaller grains by diffusion or recoil.

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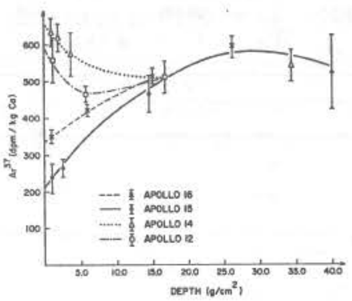

Fig. 1. The Ar^{37}/Ca ratio as a function of depth for material from the Apollo 12, 14, 15, and 16 missions

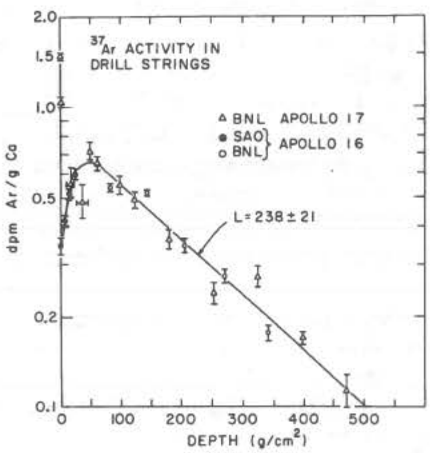

Fig. 2. Argon-37 as a function of the depth in the Apollo 16 and 17 deep drill strings.

Table 1. Solar-flare-produced ^{37}Ar from Ca and solar-flare proton (> 60 MeV) fluxes from space-probe data.

Apollo (Date)	Solar-Flare* Date	$\left[\frac{\Delta\,^{37}Ar}{Ca}\right]^{\dagger}$ (dpm/kg Ca)	$\left[\frac{\Delta\,^{37}Ar}{Ca}\right]^{\dagger}_{Cor.}$‡ (dpm/kg Ca)	Flare** (Protons/cm²)
12 (Nov. 19–20, 1969)	Nov. 2, 1969	300 ± 70	390 ± 90	2.0×10^7
14 (Feb. 5–6, 1971)	Jan. 24, 1971	370 ± 40	500 ± 50	2.9×10^7
15 (July 30–Aug. 2, 1971)	None	0	0	0
16 (Apr. 21–24, 1972)	Apr. 19, 1972	95 ± 35	98 ± 38	0.5×10^7
17 (Dec. 11–14, 1972)	Aug. 4–9, 1972	2060 ± 100	28000 ± 150	2.3×10^{10}

*Flare of significance preceding Apollo mission.

† $\frac{\Delta\,^{37}Ar}{Ca} = \left[\left(\frac{^{37}Ar}{Ca}\right) - \left(\frac{^{37}Ar}{Ca}\right)_{15}\right]$ for 0 to ~2 g cm^{-2} at the time of recovery.

‡Corrected to solar-flare date.

**Integrated flux (> 60 MeV) over 2π (Bostrom, 1971, 1973, Solar Geophysical Data).

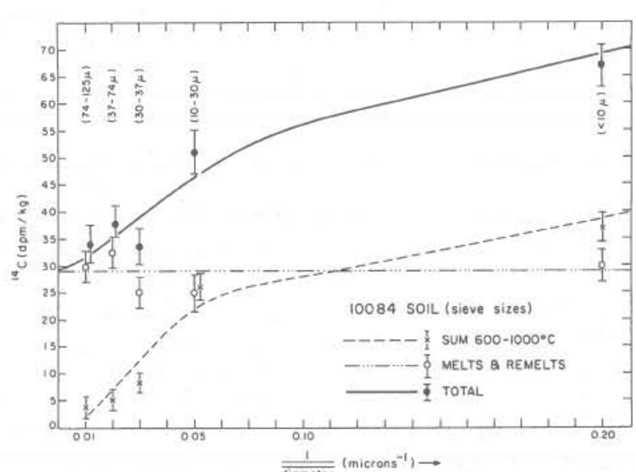

Fig. 3. Below melting, above melting, and total ^{14}C from size fractions of 10084 soil.

RADIONUCLIDES IN LUNAR SAMPLES

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^{14}C is essentially produced by the $^{16}O(p,3p)$ ^{14}C reaction in lunar samples. Begemann et al. (7) measured excess ^{14}C on the top of rock 12053; they found 72 dpm/kg in the top 0.5 cm compared to 33 and 30 dpm/kg at greater depths. Their depth profile could not be interpreted as galactic and solar cosmic-ray interactions unless solar cosmic rays were much more intense during the past 10^4 yr than during recent times. Fireman et al. (8) found that ^{14}C was released in 600–1000°C heatings of lunar surface soils are large compared to subsurface soils. Chang et al. (9), Gibson and Moore (10), and Simoneit et al. (11) showed that the carbon compounds in lunar soils are released principally between 500 and 1200°C and interpreted both the amounts and the temperature-release patterns to result from carbon implantation. There are two processes that can account for the carbon: solar-wind implantation and carbon condensation from meteor impacts. The amount of ^{14}C condensed on lunar soil from the impact vapors is negligible. Fireman et al. (8) therefore interpreted the 600–1000°C ^{14}C from soils as solar-wind implanted. Skim soil (0 to ~1 cm depth had more 600–1000°C ^{14}C than scooped soil (0 to ~5 cm depth) according to Fireman et al. (8) and the excess in the skim soil was approximately equal to the excess ^{14}C on the top of rock 12053.

We therefore investigated ^{14}C as a function of grain-size and release-temperature in soil 10084. Fig. 3 gives the results. There is twice as much ^{14}C in the $< 10\,\mu$ fraction than in the $> 30\,\mu$ fraction. On the basis of these results I concluded (12) that approximately half of the ^{14}C in the $< 10\,\mu$ size fraction was solar-wind implanted. The ~35 dpm/kg of ^{14}C in the $> 30\,\mu$ grain size fractions is larger than would be expected on the basis of galactic and solar flare proton interactions unless the solar-flare flux averaged over the past 10^4 yr were at least three times higher than averaged over the past 3 solar-cycles or that the solar-flare differential energy spectrum averaged over 10^4 yr is harder than $1/E^3$.

I feel that it is important to have confirmatory experimental evidence on the ^{14}C grain-size dependence in lunar surface soil samples. I have therefore undertaken a collaborative effort with R.W. Stoenner of Brookhaven National Laboratory. Stoenner has measured ^{14}C activities in small terrestrial iron samples in order to date ancient iron relics. Stoenner's counting technique is identical to mine; his extraction technique involves heating the samples in a stream of oxygen while mine involves heating the samples in the presence of a small amount of CO_2 carrier. Results of the collaborative effort on lunar surface soil 14163 will be presented.

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MODULATION OF GALACTIC COSMIC RAYS. L. A. Fisk, Department of Physics, University of New Hampshire, Durham, NH 03824

Studies of the solar modulation of galactic cosmic rays are central to many studies of solar variability. For example, ^{14}C is produced by medium-energy cosmic rays interacting with the atmosphere. The long-term variation in the ^{14}C content in tree rings is then a measure of long-term variations in cosmic-ray flux, which in turn is being modulated by variations in solar and heliospheric conditions. Thus we can use ^{14}C measurements to tell us about changing conditions on the Sun only if we understand the causes of the solar modulation of cosmic rays. It is an unfortunate fact, however, that our current knowledge of solar modulation is not adequate for this task. We do not know at present what changes on the Sun or in the heliosphere to produce the cosmic-ray changes.

In this paper the current theory for the solar modulation of galactic cosmic rays is reviewed. Each of the physical processes which are believed to be of significance--diffusion, convection, adiabatic deceleration, and drifts--are discussed and their importance illustrated with results of numerical models. Current thinking on how these processes may vary over the solar cycles to yield the observed cosmic-ray changes is summarized.

It is shown that cosmic-ray modulation may depend sensitively on conditions at high heliographic latitudes. Thus, an accurate understanding of solar modulation may have to await the Solar Polar Mission, which will perform the first survey of the heliosphere in three dimensions.

SOLAR LUMINOSITY VARIATION ON SHORT TIME SCALES: OBSERVATIONAL EVIDENCE AND BASIC MECHANISMS; P. V. Foukal, AER, Inc., Cambridge, MA 02139

The behavior of solar luminosity on time scales between 10^2 and 10^9 secs has been studied in a number of ways since regular monitoring of solar flux began at the beginning of this century. Besides radiometry of the solar constant, S, from below and above the atmosphere, other techniques include photometry of reflected light from solar system bodies, and synoptic monitoring of solar limb darkening, and also of certain temperature sensitive photospheric absorption lines.

The large relative changes of flux in the X-ray, ultraviolet and radio frequency regions, associated with magnetic activity in the chromosphere and corona, most probably represent low level variations of total luminosity. But their amplitude is below 1×10^{-4} of S, thus below the present detection threshold of non-selective radiometers.

Both the solar constant measurements and the absorption line monitoring indicate changes on time scales of days at a p to p level of about 7×10^{-4} of S. Recent analysis of the daily Smithsonian (APO) ground based flux data from 1923-1952 shows that these variations exhibit a significant recurrence with solar rotation. The flux decreases with area of dark spots, and increases with area of bright faculae, indicating variations of S caused by changing magnetic fields.

On longer time scales, the Smithsonian (APO) data, and also individual measurements from aircraft, balloons, rockets and satellites since 1961, have demonstrated that S varies over a range of less than 1% in half a century. But the possible existence of slow variations within this limit, yet still at a level of significance to climate, remains a controversial issue. Rocket and balloon measurements suggest an increase of about 0.2-0.4% between data taken in 1968 and 1976, and later remeasurements in 1978. But a similar radiometer on the Nimbus 6 spacecraft indicates no increase between 1976 and 1978. The increase is also somewhat above the limit set by earlier covariance analysis of 30 yrs of the daily observations from the two best APO stations between 1923-1952. Between 1975 and 1978, the line depth monitoring indicates a decrease of T_{eff} corresponding to a drop of S of about 0.6%. Thus accurate radiometry at this level over years and decades continues to pose an important experimental challenge.

A number of mechanisms might cause detectable variations of S. Obstruction of convective heat flow by large magnetic flux tubes emerging to the photosphere might be expected to yield a modulation on time scales of days. Heat flow diversion into kinetic and potential energy of global scale convection could produce stochastic variations of convective efficiency on time

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scales of months. The intensification of sub-photospheric magnetic fields during the 11 yr cycle requires a power input derived ultimately from solar luminosity on time scales of years. Variable wave heating of the photosphere may also play a role.

On theoretical grounds, a truly constant solar luminosity below the 0.1% level would be more surprising than a broad spectrum of variations, for which there is increasing evidence. Close study of these low-level changes is likely to yield a better understanding of how the sun's luminosity changes, while continuing to provide a history of solar constant behavior on the longer time scales, which is likely to prove increasingly useful to climate studies.

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LONG-TERM VARIATIONS IN THE SOLAR DYNAMO. P. A. Gilman, High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307

There seems to be little doubt that the sun's observable magnetic field is maintained by a convectively driven nonlinear dynamo. However, the theory of the solar dynamo is not good enough yet to make theoretical predictions about its long term behavior, except by use of ad hoc and highly parameterized models. Recent dynamo calculations based more directly on the laws of fluid motion have revealed significant contradictions in the assumptions on which earlier models were based. We will review some of the history of solar dynamo theory, show where the difficulties arise and how they might be resolved. We will also discuss the possibility that the envelope of the solar cycle is inherently unpredictable, due to the stochastic nature of the motions driving the solar dynamo, and the feedback of the induced magnetic fields on the flow.

Two goals of solar dynamo research that are important for the topic of this meeting are to understand how that part of the sun's magnetic field which reaches interplanetary space varies with the envelope of the solar cycle, and to estimate how much and what kind of variations in solar luminosity might be expected. In both cases, the observational clues are fragmentary, and the theory is not yet sufficiently developed to make reliable quantitative inferences. We will suggest what might be useful for making further progress.

CHARACTERISTICS OF ANCIENT SOLAR FLARE HEAVY NUCLEI. J. N. Goswami[1], D. Lal[1] and J. D. Macdougall, Scripps Institution of Oceanography, La Jolla, CA 92093 ([1]Also Physical Research Laboratory, Ahmedabad, India)

The moon and some meteorites contain a fossil record of solar flare characteristics in the form of charged particle tracks in mineral grains. By measuring depth gradients and length distributions of such tracks in grains exposed to solar flare irradiation with negligible shielding, it is possible to reconstruct energy spectra and composition of the bombarding particles. The common silicate mineral species of meteorites and the lunar regolith record only tracks produced by iron group and heavier nuclei, so that the information obtained is limited to heavy nuclei.

In this report we will discuss results of track measurements made in olivine $[(Mg,Fe)_2SiO_4]$ crystals extracted from carbonaceous chondrites. It has been known for some time (e.g. 1) that these meteorites contain "track-rich" grains, irradiated by solar flares before their incorporation into the meteorites. Recently it has been shown that the compaction of several of these meteorites took place $\geqslant 4 \times 10^9$ yrs ago (2), indicating that the solar flare records in the irradiated crystals date from the earliest part of the sun's history. With present day production rates, it can be estimated that the average exposure duration for the irradiated grains was 10^2 - 10^3 solar cycles. Thus the meteoritic crystals provide a unique record of averaged solar flare characteristics during the early history of the solar system.

Experimental methods. Three meteorites, Murchison, Murray and Cold Bokkeveld, with estimated compaction age of about 4.4 b.y. (2) were chosen for this work. A few percent of the olivine crystals from each of these meteorites contain solar flare tracks; from these a selection was made to include grains having a variety of exposure durations. Based on calibration experiments by us and results of Price et al. (3) tracks having lengths $\geqslant 20\ \mu m$ under normal etching conditions were identified as VVH nuclei tracks. Following the TINT (track-in-track) method (4), and using accelerator-produced Kr-ion tracks as channels for etching fossil iron-group tracks fully contained within the volume of the detector, we found VH group track lengths to range between 6.5 and 14.5 μm, with a peak at 11.5 μm. Price et al. (3) found a total recordable track length of 13.5 μm for fresh iron ion tracks in olivine, indicating that track lengths in the meteoritic olivines have been reduced by $\leqslant 15\%$ over 4.4 b.y.

Results. The track density gradients measured in grains examined for this work range from very close to that expected for present day solar flare radiation (as measured on the lunar surface, e.g. 5) to profiles with much flatter slopes. Since some shielding is probable during exposure of these grains, it is unlikely that changes in spectral shape of the solar flare heavy nuclei produced the flatter slopes observed in some grains, although this alternative cannot be ruled out. The observed profiles would require variable shielding, from a few to a few tens of microns of material of similar composition to the grains themselves. The fact that the steepest profiles are very close in slope to that expected from contemporary solar flare radiation implies that production, acceleration and propagation mechanisms were similar at $\sim$ 4.4 b.y. ago to those operating today.

The absolute flux of the ancient solar flare heavy nuclei is unknown, as there is no clear way to estimate the durations of exposure of the meteoritic crystals. If it is assumed that the averaged irradiation intensity for these grains was similar to that deduced for the present from Surveyor data (6-8), exposure durations are calculated to range from a few hundred to a few thousand years, corresponding roughly to 10^2 - 10^3 solar cycles. Thus short term ($<<10^3$ yr) variations in the spectral shape of the ancient solar flare heavy nuclei cannot be ruled out from our data.

Our results for composition of the ancient solar flare heavy nuclei, given in terms of VVH/VH, are tabulated in Table 1 and plotted in Fig. 1, together with earlier data by a similar technique obtained by Bhandari et al. (9) for lunar rock and soil samples. These data refer to a more recent time scale than do the meteorite results. The most obvious feature of our data is the rapid rise in VVH/VH at low energies, indicating a preferential enrichment of heavy nuclei in the ancient solar flares. In addition, although there is a general overlap between the meteoritic and lunar data, some carbonaceous chondrite measurements give considerably higher values for ρ_{VVH}/ρ_{VH} at low energies. The meteoritic data also appear to be more variable.

The observed enhancement of VVH nuclei over iron group nuclei at low energies implies that the preferential enhancement of low energy heavy ions seen in contemporary solar flare

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Table 1. ρ_{VVH}/ρ_{VH} values in solar flare irradiated olivine grains from carbonaceous chondrites

Sample Details	Energy Interval (MeV/n)	ρ_{VVH}/ρ_{VH} (x 10^{-3})
MURCHISON		
MR-15-4	6 - 18	7.6±2.0
MG-3	7 - 15	6.2±1.2
MUR-63-15	5 - 7.5	11.3±2.2
MUR-5387-10	5.5 - 9.0	23.8±4.3
MURRAY		
MAY-1	> 12	14.0±3.5
MAY-17	8 - 10.5	9.1±2.6
MAY-22	7.5 - 12	15.6±3.2
MAY-576-8	> 12	3.8±1.0
MY-9	6 - 11	12.0±3.5
COLD BOKKEVELD		
CB-1	6 - 11	9.0±2.0

radiation is a long term phenomenon which has continued since the early history of the solar system. Although conversion of the observed track density ratio (i.e. ρ_{VVH}/ρ_{VH}) to the abundance ratio of these nuclei is somewhat uncertain due to uncertainties in the mean total recordable track length of the VVH nuclei, we estimate a value of $\geqslant 7\times10^{-3}$ for the abundance ratio $(Z \geqslant 30)/(22 \leqslant Z \leqslant 28)$, corresponding to $\rho_{VVH}/\rho_{VH} \simeq 10^{-2}$, in the energy interval of 6 - 10 MeV/n. This value is higher by a factor of $\geqslant 5$, than the photospheric ratio of 1.28 x 10^{-3} (10), and can be compared with the enhancement factors of ~ 40 and ~ 120 for $Z \geqslant 32$ and $Z \geqslant 44$ nuclei over iron group nuclei at energies of 0.3 - 1.0 and 0.6 - 2.0 MeV/n respectively in contemporary solar flare radiation (11).

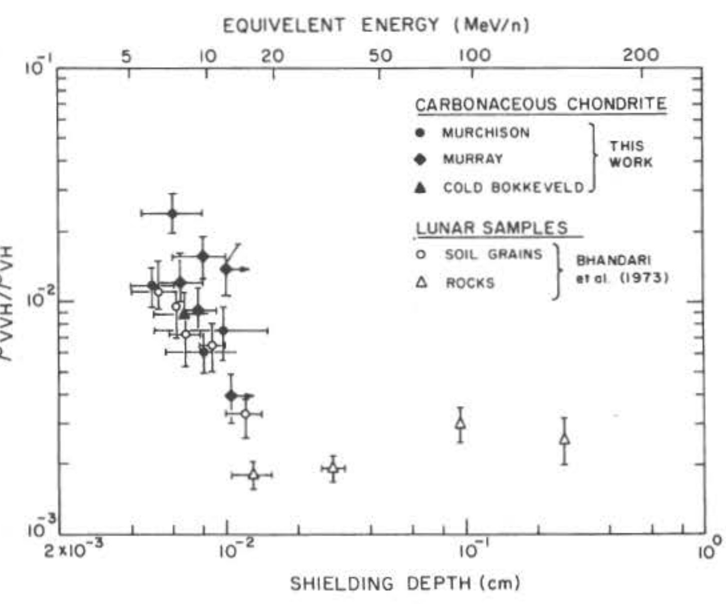

FIGURE 1: The ratio of tracks due to VVH-group nuclei to those due to VH-group nuclei plotted as a function of shielding depth (energy). Also shown are the lunar data of Bhandari et al. (1973).

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The facts that meteoritic grains show variable ρ_{VVH}/ρ_{VH} at a given energy, even taking into account shielding differences, and that some grains exhibit values considerably above the contemporary ratio, suggest possible variations in the long-term (10^3 yr) averaged values for the enhancement factor in spite of a similar spectral shape for the VH nuclei. This would imply changes in solar flare activity on time scales of 10^2 - 10^3 years. This possibility is supported by the observed heavy ion enhancement pattern in contemporary flare radiation in which higher values of the enhancement factor, as well as enhancement extending to higher energies, are generally associated with large flares (12, 13). Thus one can speculate that the grains showing high values of ρ_{VVH}/ρ_{VH} were exposed to solar flare radiations when the time averaged solar flare activity was much higher than during the periods of irradiation of other grains.

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SOLAR FLARE PROTON AND HEAVY NUCLEI FLUXES IN RECENT AND ANCIENT PAST. J.N. Goswami, D. Lal, M.N. Rao and T.R. Venkatesan, Physical Research Laboratory, Ahmedabad 380 009 India

Particle track and noble gas studies of selected lunar and meteorite samples have been carried out by us to obtain information on the short- ($\sim 10^4$ years) and long-term ($\geqslant 10^6$ years) averaged solar flare proton and heavy nuclei fluxes in recent (< 10 m.y.) and ancient (up to 4 b.y. before present) past. In this paper we report some of the important results obtained in these studies.

For obtaining solar cosmic ray (SCR) proton fluxes in the recent past, lunar rock samples with low galactic cosmic ray (GCR) exposure ages have been selected for noble gas studies. In the case of particle tracks, after a detailed survey of a group of rock samples, those showing simple exposure history have been selected for obtaining SCR heavy nuclei fluxes. For obtaining short- as well as long-term averaged SCR fluxes in the past we have mainly studied surface as well as drill core lunar soil samples and gas-rich meteorites. The experimental approach used in the noble gas studies is oriented to achieve an accurate partitioning of the total gas content into SCR, GCR and trapped components, based on the data obtained from step-wise heating mass-spectrometric analysis. Such a partitioning is relatively straight-forward in the case of rock samples, where one can choose samples from different shielding depths (1). However in the case of lunar soil samples, the complex mixing and gardening processes operating in the lunar regolith makes such a partitioning difficult. We have developed methods which involve removal of the surficial solar-wind in soil samples by selective chemical etching of monomineralic component prior to mass-spectrometric analysis (2). In the case of particle track studies we use the standard procedures for revelation of tracks in common silicate minerals. Both optical and electron microscopy techniques are used. The "total recordable track length" criterion and the "track shape" methods are used for identifying atomic number of track forming nuclei. Accelerator heavy ion irradiations are performed for calibration.

Time-averaged SCR particle fluxes in the recent past (< 10 m.y.). Three samples of rock 61016 from known depths have been analyzed for obtaining the SCR produced Ne and Ar isotopic contents. The SCR Ne-21 values obtained are 0.125 ± 0.021; 0.058 ± 0.009 and 0.023 ± 0.004 (all in 10^{-8}cc STP/g) respectively, in samples representing the depth intervals 0 - 0.6 g/cm^2; 1.2 - 2.1 g/cm^2 and 4.8 - 5.4 g/cm^2. The corresponding SCR Ar-38 contents are 0.688 ± 0.081; 0.229 ± 0.027; 0.066 ± 0.008 (all in 10^{-8}cc STP/g) respectively (1). Using a time-averaged SCR proton flux $J(> 10$ MeV$)=70$ protons/cm^2 sec with characteristic rigidity $R_o=100$ MV (3) and production rates of interest (4) we obtain a noble gas SCR exposure age of (1.23 ± 0.20) m.y. from Ne-21 results and (1.7 ± 0.2) m.y. from Ar-38 results for rock 61016. These ages and particularly the Ar-38 age is in good agreement with the SCR age of 1.5 m.y. for this rock based on particle track data (5). However, the SCR proton flux used above is lower by $\sim 50\%$ than the estimate made by Bhandari et al. (5) based on Al-26 data in six lunar rocks. In order to understand this discrepancy we now plan to carry out SCR produced noble gas studies in rocks with short GCR exposure ages in which the SCR exposure ages determined by radionuclide data are similar to the GCR ages.

The evaluation of SCR heavy nuclei ($Z \geqslant 20$) energy spectrum based on particle track studies of lunar rocks is hampered by several factors such as track recording characteristics; annealing and erosion effects and lack of independent measure of exposure time. The best estimate of long-term average flux of solar flare heavy nuclei during the last few m.y. obtained by us (6) indicate that: i) the long-term averaged absolute flux can be almost an order of magnitude lower than the present day estimate based on revised Surveyor data (7), ii) the spectral shape is similar to contemporary value with a power index close to -3, iii) the transition zone from SCR to interplanetary component is around 20 MeV/n, unlike the case of protons where it takes place at ~ 100 MeV/n.

SCR particle fluxes in last 1 b.y. and at $\geqslant 4$ b.y. before present. The study of lunar surface soil samples allows us to obtain information on integrated SCR fluxes during the last few tens of million years whereas the study of samples taken from different depths in the Apollo and Luna drill core soil column gives us this information for different widely-spaced epochs in the past billion years. We have so far determined SCR produced noble gas contents in several surface as well as drill core soil samples to delineate their SCR exposure histories. Unlike the case of rocks, the quantitative analysis of noble gas data in soil samples to obtain long-term averaged SCR fluxes is hindered by their complex evolutionary history. However, using the particle track data from the same set of samples, one can obtain integrated near-surface (< few cm) exposure age of the soil samples which should serve as an upper limit for the estimation of the SCR exposure age. We give in Table 1 the noble gas SCR exposure ages based on the proton flux noted earlier and the particle track based integrated near-surface exposure ages for the soil samples analyzed by us. Although the particle track data suffer from saturation effect for exposure ages > 50 million years, the noble gas SCR exposure ages are similar to or less than the track-based exposure ages. This result *qualitatively* suggests that the time-averaged solar flare proton fluxes during the epochs in the past in which these samples received their solar flare irradiations could not have been lower than the average SCR proton flux derived for last few m.y. For obtaining a more quantitative information on possible changes in the long-term averaged spectral shape and intensity of solar flare protons we plan to concentrate our efforts on accurate determination of the isotopic ratios of SCR produced noble gases in samples having different exposure histories. The study of solar flare heavy nuclei tracks is mainly aimed at obtaining information on possible temporal and spatial variations in solar flare intensity, composition and energy spectra in the past. We have analyzed solar flare irradiated grains from surface and drill core soil samples taken at Apollo 12, 15 and 17 sites which span the time-scals up to 1 b.y. Analysis of solar flre irradiated grains extracted from several C2 chondrites (Murchison, Murray and Cold Bokkeveld) provides similar information during the very early history of the solar system (8). As in the case of noble gas studies, the lack of an independent SCR chronometer does not allow us to obtain quantitative information on the absolute fluxes of ancient solar flare heavy nuclei. However, the observed track records in both lunar and meteorite samples rule out long-term ($\geqslant 10^4$ yrs) changes in the spectral shape in the solar flare heavy nuclei fluxes. The similarity in the deduced spectral shape, therefore, indicates similar production, acceleration and propagation mechanism of solar flare heavy nuclei at different widely-separated epochs spanning the last 4 b.y. (8).

The study of solar flare heavy nuclei composition using different experimental approaches shows that the preferential enrichment of solar flare heavy nuclei seen in contemporary solar flares persisted in the recent and ancient past. The abundance ratio of $Z \geqslant 30$ nuclei over the Fe group nuclei increases from the photospheric value at energies < 20 MeV/n and the relative enhancement was found to increase with decreasing energy down to ~ 2 MeV/n, below which the enhancement factor either levels off or drops down. Our recent analysis of solar flare irradiated grains in carbonaceous chondrites (8) indicates higher value for the above abundance ratio, compared to lunar values at similar energy intervals. Considering the enhancement systematics of low energy solar flare heavy ions as obtained in contemporary experiments (9) the above observation seems to indicate a higher level of solar flare activity during the period, when the carbonaceous chondrites received their solar flare irradiation -- most probably during the very early history of the solar system. (1) Rao M.N. et al. (1979) *Proc. Lunar Planet. Sci. Conf. 10th* (in press). (2) Bhai N. B. et al. (1978) *Proc. Lunar Planet. Sci. Conf. 9th, p. 1629-1645. (3) Kohl C. P. et al. (1978) Proc. Lunar Planet. Sci. Conf. 9th, p. 2299-2310. (4) Hohenberg C. M. et al. (1978) Proc. Lunar Planet. Sci. Conf. 9th,* p. 2311-2344. (5) Bhandari N. et al. (1976) *Proc. Lunar Sci. Conf. 7th,* p. 513-523. (6) Bhandari N. et al. (1973) *Astrophys. J.* **185**, 975. (7) Hutcheon I.D. et al. (1974) *Proc. Lunar Sci. Conf. 5th,* p. 2561-2576. (8) Goswami J. N. et al. (1979) *Proc. 16th Intern. Conf. Cosmic Rays,* Tokyo (in press). (9) Crawford H. J. (1975) *Ap. J.* **195**, 213-221.

Table 1. SCR/Surface exposure ages of lunar soils

Soil	Mineral (size in μm)	SCR exposure age (m.y.) Ne-21	Xe-132	Track based surface exposure age (m.y.)
69921	feldspars (200-1000)	73±10	80±12	⩾ 50
14148	feldspars (40-90)	18± 7	53±16	20
	(90-200)	22± 9	15± 5	
24087	feldspars (40-200)	128±43	-	
	(200-1000)	48±16	-	⩾100
14163	bulk	66	43	⩾ 60

SOLAR WIND NOBLE GASES AND SPUTTERING, SOLAR FLARE PARTICLE TRACKS, METEOROID IMPACT CRATERS, AND DUST ON LUNAR SURFACES. Jack B. Hartung, Dept. of Earth and Space Sciences, State University of New York at Stony Brook, Stony Brook, New York 11794

Any process which leaves a measurable record on a lunar sample surface may be considered an exposure time "clock." Such processes include accumulation of solar wind particles, the effects of sputtering by solar wind particles, iron-group energetic particle tracks, implanted lunar "atmospheric" particles, cosmogenic radioactive nuclides, meteoroid impact craters, accreta and dust. The rate of one process compared to that of another, a relative rate, may be determined by measuring the accumulated effects of both processes on the same surface. The more difficult task of determining absolute rates requires that an independent and absolute measure of a rate be available. The main objective of the work reviewed here has been to determine the absolute rates of the processes mentioned and, to the extent possible, any variations in these rates on time scales of 10^2 to 10^5 years. An average rate for the exposure lifetime of a surface may be determined based on one measurement. Variations in rates can only be determined if numerous measurements are made over different time periods.

Solar Wind Noble Gases and Lunar "Atmospheric" ^{40}Ar

Areal concentrations of ^{4}He, ^{20}Ne, ^{22}Ne, ^{36}Ar, ^{38}Ar, and ^{40}Ar have been measured on 75 μm-diameter spots on one exposed lunar rock surface (1). These data together with absolute flux data from the Solar Wind Composition experiment (2) yield apparent exposure times which are lower for the lighter elements. This trend indicates that ^{4}He, ^{20}Ne, and possibly ^{36}Ar is lost from exposed surfaces. Based on analysis of the distribution of solar ^{36}Ar and lunar ^{40}Ar on sunlit and shaded surfaces, the loss mechanism may be sputtering or diffusion from the rock and thermal escape from the Moon. For a sputter rate of 3×10^{-9} mm/yr (3) and an estimated implantation depth of 3×10^{-5} mm ^{36}Ar would approach equilibrium with respect to loss by sputtering after only 10^4 years. Thus variations in solar wind flux may be available for study only for times less than this.

Sputter Erosion by Solar Wind Ions

Lunar surface features are modified by sputter removal of atoms from one location and deposition of those atoms at another. In principle, rates of solar wind sputtering can be determined relative to those of other surface processes, such as accreta or microcrater accumulation. The number of accreta particles of a certain size (height) in equilibrium with respect to sputtering depends upon the relative rates of accreta production and loss by sputtering. The characteristic size of surface features, the numbers of which are just in equilibrium with respect to loss by sputtering, depends upon the duration of exposure. McDonnell (3) has shown for one sample that sputter equilibrium was just reached for accreta particles 6×10^{-4} mm in diameter. Based on an independently determined exposure time for the surface an average solar wind sputter erosion rate over a period of about 10^5 years of 3.1×10^{-9} mm/yr was found. Similar work by Morrison and Zinner (4) yielded a maximum rate of 3×10^{-9} mm/yr averaged over about 10^4 years.

Solar Flare Tracks

Etchable ionization damage tracks of iron-group nuclei accelerated during solar flare events are present in the upper mm of exposed lunar samples. Considerable effort has been devoted to obtaining absolute rates for the production of solar flare tracks, so that this "clock" could be used to measure the near-surface exposure times of many lunar samples. Initially, tracks measured in the glass filter from the Surveyor III camera system exposed for 2.5 years on the Moon provided absolute rate data (5). Because this exposure was short compared to the known 11-year solar cycle and because of difficulties in interpreting the track data in the Surveyor glass, later workers (6,7) relied on exposure ages derived using galactic cosmic ray track production rates (8) or the accumulation of cosmogenic krypton isotopes (9), one of which is radioactive with a known decay rate, thus providing the basis for the absolute rate determinations. These calibration efforts required very careful sample selection because each of these processes corresponds to different characteristic depths (solar flare tracks, < 1 mm; galactic cosmic ray tracks, a few cm; cosmogenic Kr, tens of cm); and very few lunar samples have had such a simple regolith history that exposure corresponding to each of these depths occurred for the same length of time. These efforts assumed that the production rate of solar flare tracks did not vary on a time scale comparable to the exposure time for the samples used (10^4 - 10^6 years).

Meteoroid Impact Craters

Meteoroid fluxes or impact crater production rates are independent from any solar process for craters larger than about 10^{-2} mm in diameter. Early workers related microcrater populations to a single exposure age, usually based on solar flare tracks, for a surface. These results led to several suggestions that the average meteoroid flux over about 10^5 years was lower than present values based on satellite-borne measurements, but for a variety of reasons these interpretations have not survived (10). Later, solar flare tracks were successfully observed in individual sub-mm-sized glass-lined microcrater pits (11). Exposure ages estimated for over fifty individual craters were concentrated toward younger ages. Based on the assumption of a constant solar flare track production rate, this suggested a lower flux of meteoroids in the past. Zook et al. (12) argued that the meteoroid flux was constant and that the data could be explained by higher solar flare production rates in the past, more than a factor of ten change in a period of about 10^4 years. More recently, Hartung and Comstock (13) have pointed out that such relative microcrater age distributions, that is, distributions showing more young than old craters on surfaces not approaching equilibrium with respect to crater superposition, may be due to fine-scale accumulations of dust on surfaces. Relative microcrater age distributions using accumulation of solar flare tracks, micrometer-sized impact pits, and accreta particles as "clocks" have shown more apparently young than old craters. Morrison and Zinner (4) have compared densities of 10^{-4} mm-diameter impact pits and solar flare tracks at a depth of 10^{-1} mm in four samples and found a linear correlation exists over a range of values which differ by a factor of 30 for either parameter. Although the rates of both processes could vary sympathetically, the most reasonable interpretation is that the rates of both processes have been essentially constant.

Effect of Dust Layer

This result is somewhat at odds with the idea put forward by Hartung et al. (14) that a layer of fine dust on a surface may inhibit the accumulation of 10^{-4} mm diameter pits while permitting the accumulation of tracks at a depth of 10^{-1} mm. Because of the prospect of unknown amounts of loose dust on sample surfaces, comparison of the rates of processes with different characteristic depths of occurrence may not be legitimate. Exposure times derived using processes occurring at deeper characteristic depths are necessarily longer than for near-surface processes. According to this line of reasoning, the following sequence of processes, listed in descending order of average exposure time measured for the same sample and the corresponding characteristic depths, should prevail: 1) cosmogenic noble gases, 2) galactic cosmic ray tracks, 3) mm-sized microcraters, 4) solar flare tracks and solar cosmic ray effects, 5) 10^{-3} mm-sized microcraters, 6) solar wind sputtering of accreta, 7) accumulation of solar wind atoms. If rates of two different processes are to be compared, then samples must be carefully selected, so that actual exposure times for both processes were the same.

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THERMAL METAMORPHOSIS OF THE ASTEROIDS AND THE MOON AS A POSSIBLE RELICT OF A DENSE PRIMORDIAL SOLAR WIND. Floyd Herbert and C.P. Sonett*, Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, Az. 85721 (*also Dept. of Planetary Sciences).

Relevant Empirical Background. Modern telescopic observation of asteroids has shown that asteroids fall into a small number of taxonomic classes which appear to reveal the chemical composition of the individual asteroidal surfaces.[1] Some of these asteroids (Vesta, the TRIAD[2] S & M classes) appear igneous; others (Ceres, Pallas, the C class) appear non-igneous (The C class resembles carbonaceous chondritic meteorites, which are thought to be relatively unmodified samples of primordial solar system material). There are systematic trends in the distribution of these classes in space and size, some of which can be seen in Fig. 1, a scatter diagram of individual asteroids, identified by type (or name), taken from TRIAD.[2] In particular, the S class is concentrated towards small heliocentric distance and those that exist at medium distance are concentrated toward smaller size.

An interesting feature of the S class is that it seems to be a compositional group representing objects heterogeneously composed of metallic iron and igneous rock (primarily olivines and pyroxenes), possibly the exposed interiors of differentiated and fragmented asteroids.[3] Recent work on orbital-element families of asteroids, which are presumably fragments of a once-unitary body, indicates that some families contain many S objects but no identifiable core remnant (M object).[4] Wood[5] has also shown that the frequency of certain stony-iron meteorites (Pallasites) is higher than one would expect from the surface-to-volume ratio of iron cores in spherically symmetric planets. These observations suggest that when iron separated out in differentiating asteroids it did not always or even usually segregate itself into unitary iron cores.

Analysis of meteorites has led to some inferences about thermal histories of parent bodies that also bear on thermal evolutionary calculations. It has been known for a long time that certain iron meteorites seemed to have cooled through the 400-600°C range relatively slowly,[6] perhaps because of an insulating overburden. Recently Wood[7] has noted evidence for much faster cooling at higher temperatures, suggesting (among other possibilities) highly inhomogeneous original temperature distributions. Mittlefehldt[8] has modelled geochemically the formation of basaltic achondrites and argues that these igneous meteorites show among other things that the degree of partial melting was highly variable, some source regions were melted more than once and some igneous differentiates have been remelted, leading him to conclude that the heat source was spatially inhomogeneous and sporadic in time. He estimates a total length for the epoch of $\approx 2\times10^8$ years.

In the case of the moon it has been argued for some time that the outer crust was originally melted to some depth,[9] but probably not completely to the core,[10] the last fraction finally freezing after 2×10^8 years.[11]

Thermal Models. Thermal evolutionary models were constructed of the moon and asteroids in an attempt to interpret the observational data detailed above. Asteroid models of various radius and distance were constructed as an ensemble. For simplicity conditions were assumed such that transverse magnetic induction was dominant. The initial composition was assumed to be similar to carbonaceous chondrite.

Contour plots of the maximum asteroid temperatures attained with two particular parameterizations are shown in Figs. 2 and 3 with the positions of Ceres, Vesta and Pallas shown. In the model of Fig. 2, the environmental

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temperature at 1 AU was assumed to be 200°C (about 100°C at the asteroid belt) the solar mass loss was 1/3 of the original mass, the magnetic field at the base of the corona was 100 gauss, the solar wind velocity was 400 km/s, the solar angular velocity was $10^{-4}s^{-1}$, and the radius of the base of the corona was taken equal to the present solar radius. All asteroids were assumed to have originated from material similar to C2 carbonaceous chondrite. The maximum temperatures are cut off at 1300°C to simulate melting and convection. Fig. 3 summarizes a model similar to that of Fig. 2, except that the initial asteroid belt composition was assumed similar to C1 and the solar wind motional electric field was doubled by changing the solar spin rate and coronal base height.

Both models led to total melting of Vesta. While Ceres and Pallas reached fairly high temperatures, they fell well short of melting. In the model of Fig. 2, Pallas attained a temperature markedly higher than that of Ceres. Such high temperatures would probably alter the appearance of Pallas (and possibly Ceres) from that of the typical C object, but without the drastic change of melting.

Simultaneously with each grid of asteroid models a lunar model was generated subject to the same (but scaled for solar distance) conditions. The initial lunar composition was taken as similar to model lunar enstatite.[12] The resultant evolution yielded a lunar magma ocean of depth 70-300 km, depending upon assumptions concerning electrical conductivity at melting.

Discussion. The asteroid belt temperature distributions shown in Figs. 2 and 3 appear to yield a natural explanation of why Ceres and Pallas seem non-igneous and Vesta appears to have once undergone melting. Moreover there seems to be a rough correspondence between the calculated contours and the distribution of apparently metamorphosed asteroid types. In the lunar case as well, there seems to be reasonable agreement between model and actual history.

The simple models discussed above are spherically symmetric. Investigations into more complicated geometry suggest that at these scales electrical heating possesses an instability of a self-localized character.[13] Thus the inferences of metamorphic heterogeneity discussed in the previous section seem a natural outcome of electrical heating.

If we assume, because of the general agreement between model and observation, that the thermal histories of asteroids and the moon were dominated by induction heating, we can make certain approximate inferences about the primordial solar wind. For example, depending on the isotropy of the flow, significant planetary heating appears to require a ponderable solar mass loss. The work of Mittlefehldt[8] suggests an episodic solar wind outflow extended over a total duration of 10^8 years, but perhaps confined to short intense bursts. The solar characteristics that seem to yield reasonable agreement between models and observation also suggest a high enough combination of fields and outflow that solar spin-down would be expected to have occurred primarily at an early epoch, rather than distributed over solar history. That a solar surface magnetic field significantly larger than the present one seems indicated may yield insight into the nature of the forces driving the primordial solar dynamo. For example, a stronger field might be the result of more vigorous convection (which might possibly be the cause of the larger solar wind flux as well). References: [1]E.g., McCord and Gaffey, (1974) Science 186, 352; Chapman, et al. (1975) Icarus 25, 104; Bowell et al. (1978) Icarus 35, 313. [2]Bowell et al. (1978) Icarus 33, 630. [3]McCord and Gaffey (1974) Science 186, 352; Chapman et al. (1975) Icarus 25, 104. [4]Gradie and Williams (1979) submitted to Icarus. [5]Wood (1978) Asteroids (NASA Conf.

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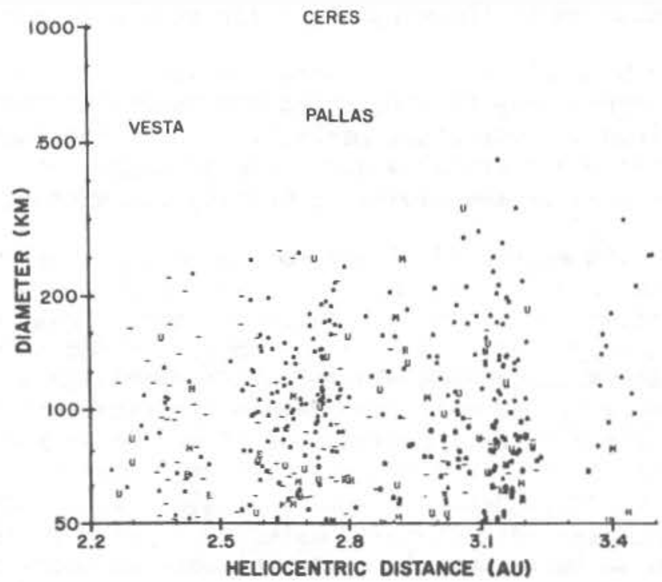

Figure 1. Sizes and distances of the largest asteroids, plotted by type. The symbol - denotes S type, the symbol * denotes C type, with the other types indicated by the appropriate letters.

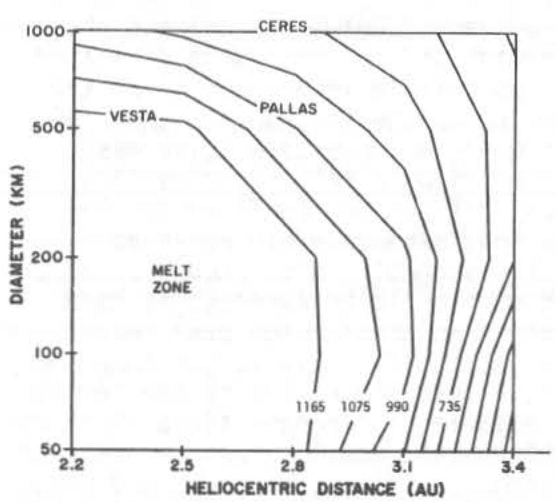

Figure 2. Contour diagram of maximum model temperatures reached by an initially C2 asteroid population.

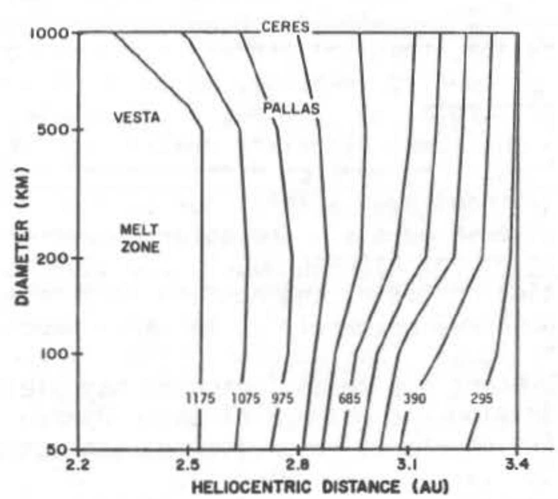

Figure 3. Contour diagrams of maximum model temperatures reached by an initially C1 asteroid population.

DID GAS-RICH METEORITES RECORD THE BEHAVIOR OF THE ANCIENT SUN?

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Gas-rich meteorites contain solar wind implanted noble gases and nuclear particle tracks, i.e., manifestations of crystalline damage due to irradiation by Fe group nuclei in solar flares. An important but as yet unanswered question is, when did the irradiation of gas-rich meteoritic material occur? Unconstrained by experimental data, some have suggested that the noble gases and particle tracks could have been acquired at any time during the last 4.5 by. If the irradiation occurred during the early epochs of solar system evolution, then the gases and tracks in meteorites could provide valuable information concerning the elemental composition and energy spectrum of the ancient solar wind. Although we cannot yet provide the absolute time at which meteorites acquired their gases and tracks, we can determine when, in terms of how far accretion must have proceeded, particles emitted by the Sun could penetrate the absorbing solar nebula to a distance of 3 AU and so leave their mark in meteoritic materials. Through the modeling efforts and calculations described below, we hope to better pinpoint "when" the irradiation could have begun and thereby determine whether or not information concerning the ancient solar wind can be extracted from gas-rich meteorites.

As a starting point we have constructed a very simple model for the absorbing nebula. It consists of two absorbing components, solid spherical "dust" particles and hydrogen gas, which are uniformly dispersed throughout a cylindrical disk of radius 3 AU and thickness 0.1 AU. The dust particles have a common diameter and are taken to be of olivine composition with the cosmic Fe/Mg ratio. The total dust mass is given as a fraction, f, of the mass currently contained in the terrestrial planets. The value of f is used to indicate, roughly, the extent to which the terrestrial planets have accreted; small values of f mean that accretion is nearly complete. The mass of absorbing gas in the nebula is specified by the density ρ_g(g/cm^3), of hydrogen in the cloud.

For a given set of conditions (size of dust particles, mass of dust and gas density) we determine whether or not a solar wind or solar flare ion is likely to survive passage through the nebula. A probability distribution is computed for the thickness of material that the ion must traverse in order to reach 3 AU. The thickness is a random quantity because of the random positions of the dust particles. Given the energy for an ion we compute its range in an absorber composed of silicate dust and hydrogen gas. These range-energy relationships were taken from standard references (1,2). The probability of penetration to 3 AU is just the probability that the random thickness is less than the ion's range.

Calculations have been made for protons of energy 0.1, 1 and 10 MeV, used to represent solar wind implantation in meteoritic materials, and Fe nuclei of energy 1 and 10 MeV/nucleon, used to represent the formation of solar flare particle tracks. In Figures 1 and 2 are shown results for the 1 MeV protons. This case illustrates most of the general features of all our calculations. The penetration probability is plotted as a function of f and the dust particle diameter. For the case of no absorbing gas (Fig. 1), penetration to 3 AU is unlikely until accretion is very nearly complete, i.e. f must be smaller than 10^{-3} or 10^{-4}. Similar results are found for solar flare Fe nuclei. For more energetic protons, (10 MeV), penetration occurs for f $\lesssim 10^{-2}$- 10^{-3}. Note that present day conditions where f $\simeq 10^{-5}$- 10^{-6} easily allow penetration.

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When a small amount of gas is added to the nebula (Fig. 2, $\rho_g = 10^{-17} g/cm^3$) penetration becomes more difficult. Note, for an assumed nebular temperature as high as 1000°K, this value of ρ_g corresponds to a gas pressure of only $\sim 5 \times 10^{-13}$ atm. If ρ_g is increased to 10^{-16} then the gas alone is sufficient to cause absorption, irrespective of f and the dust particle size. For other particle energies, the maximum value of ρ_g for which penetration can occur are shown in Table I.

These results show that meteoritic material will not begin to record information about the solar wind until only a small fraction of the mass of the terrestrial planets is left unaccreted or until particles attain dimensions of several centimeters. Also, a small quantity of absorbing gas in the nebula is sufficient to shut off the irradiation. That is, implantation of solar wind and solar flare particles in material at 3 AU could take place only under conditions more nearly resembling those in the present solar system in the solar nebula.

Studies of particle tracks contained in gas-rich meteorites strongly suggest that many of these meteorites evolved in regoliths on asteroidal-sized bodies. Some have argued that these meteorites could not have evolved in modern-day asteroid regoliths because the regoliths are very thin due to the loss of impact ejecta from the small gravity fields of asteroids. If this were true it would lend support to the idea that meteorites acquired their irradiation features during the early accretional epochs prior to the development of high velocity, erosive collisions. However, recent modeling efforts (3,4) have shown that present day asteroidal regoliths may be rather substantial; in many cases much thicker than the lunar regolith. Asteroids of a few hundred kilometers diameter provide an environment where gas-rich meteorites can obtain the observed radiation features.

In summary, our absorption calculations suggest that an early irradiation of meteoritic material was unlikely, i.e., gas-rich meteorites do not contain information about the ancient solar wind. Also, an irradiation during recent epochs is consistent with studies of asteroidal regolith evolution.

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Table I

Approximate maximum gas densities (g/cm^3) which allow penetration to 3 AU.

Energy (MeV/nuc)	protons	Fe nuclei
0.1	10^{-18}	-
1	10^{-17}	10^{-17}
10	10^{-15}	10^{-15}

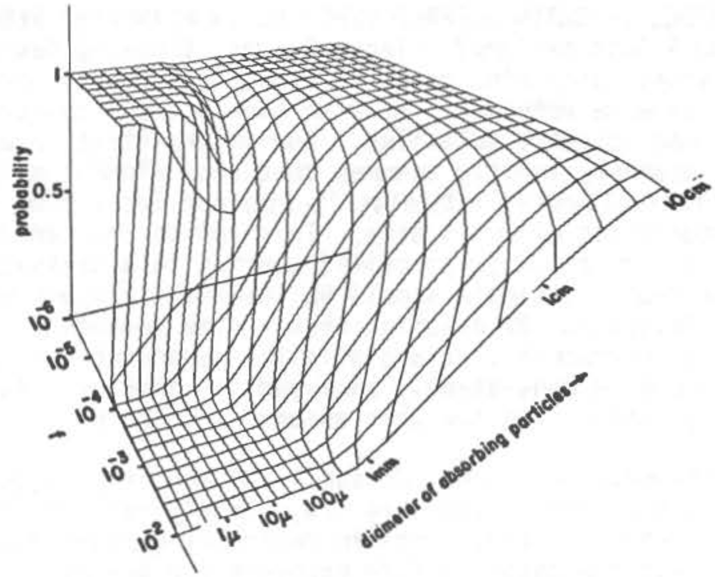

Fig. 1. Probability that a solar 1 MeV proton will penetrate a cloud of absorbing particles to a distance of 3 A.U. The probability is plotted as a function of the size of absorbing particles and the total mass of absorbers, expressed as a fraction, f, of the total mass of the terrestrial planets. Irradiation of asteroidal material is improbable until accretion is nearly complete ($\lesssim 10^{-3}$ of the mass left unaccreted as dust).

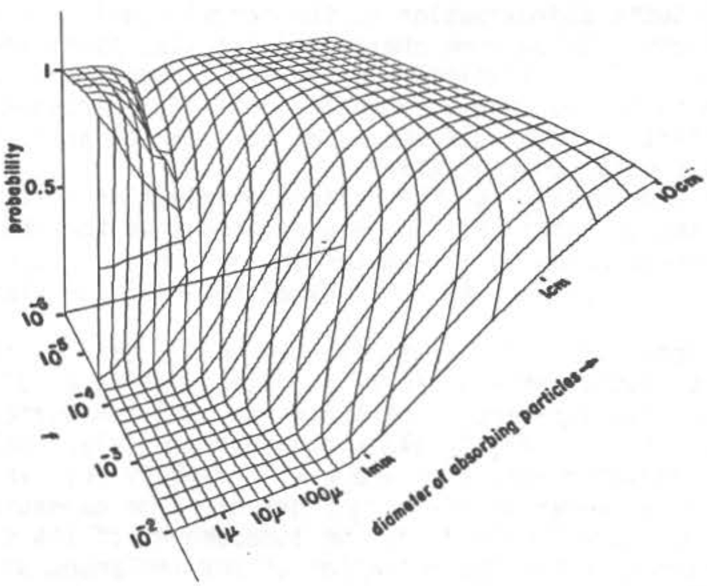

Fig. 2. Probability of penetration when a small quantity of absorbing hydrogen gas is added ($\rho_g = 10^{-17} g/cm^3$). If the density of gas is increased to $10^{-16} g/cm^3$, penetration becomes impossible.

TOWARD A MODEL OF GRAIN SURFACE EXPOSURE IN PLANETARY REGOLITHS.

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Studies of implanted solar wind gases have been vigorously pursued since the first lunar samples were returned. So also have studies concerning vapor deposited meteoritic and volcanic volatiles. During the first several years of this work, it was commonly tacitly assumed that each element of grain surface had the same statistical probability distribution for total time of direct exposure to space, regardless of grain size. This led to the expectation that the concentration of an implanted or deposited species in a grain-size separate of any particular regolith sample should be inversely proportional to the mean radius r of the fraction. By assuming that a size independent volume correlated indigeneous, cosmogenic, or agglutinitic component was also present, most available data could be consistantly analyzed in terms of this view. However, no physical justification for this assumed surface exposure law was apparent.

In a very thought-provoking paper, Criswell (1) recently suggested a completely different grain surface exposure law, closely related to the Rosiwal Principle (2) used by petrologists in determining model mineralogy of rocks. He suggested that the total surface exposure for grains in any size range should be proportional to the volume fraction of the total sample in that size range. This law appears reasonable if we assume that at any instant the actual regolith surface can be adequately approximated by an imaginary surface constructed by taking a plane through the regolith below the top layer and removing all particles which have half or more of their volume above this plane.

Upon leisurely reflection, it is clear that a surface constructed as above cannot be an adequate approximation to the actual regolith surface for very small particle sizes. Below some characteristic size particle-particle adhesive forces will exceed gravitational forces and larger grains will generally be coated with smaller ones. Boynton et al. (3) stressed the importance of this effect in their discussion of data on the grain size dependence of volatile trace metal concentrations.

From dry sieving experiments and the optical examination of dust-coated surfaces of large grains or rocks, it can be estimated that the above characteristic size corresponds to a diameter in the range 10-30μm in terrestrial gravity. In lunar gravity, this dimension would be almost doubled.

There must also necessarily be a cut-off size on the small size tail of the particle size distribution of any sample such that the total of all particles smaller than that size are insufficient to coat the surfaces of all the larger particles. It seems highly plausible that particles smaller than this cut-off and the characteristic size above will largely move in and out of the regolith surface as a veneer on the larger grains. The exposure interval for any one of these very small grains will be independent of its size leading to an exact dependence of the concentration of any implanted or vapor deposited species on 1/r.

Table 1 shows mass and surface fractions in different size ranges for one regolith sample. It appears that for this sample the exact 1/r relationship can be expected for particles below about 7μm in diameter.

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Table 1. Mass and surface fractions in different size intervals of 12001 regolith fines.

Size Interval μm	Mass Fraction	Surface Fraction
420-1000	0.063	0.002
150-420	0.155	0.010
75-150	0.170	0.026
45-75	0.139	0.041
30-45	0.167	0.079
20-30	0.058	0.041
10-20	0.088	0.104
5-10	0.117	0.278
2-5	0.025	0.129
1-2	0.011	0.141
0.75-1	0.004	0.073
0.5-0.75	0.001	0.040
0.2-0.5	0.001	0.036
0-0.2	0	0

It seems moderately plausible that particle-particle adhesive contacts are made and broken in a fairly random way for particles up to about 50μm in diameter on the moon. This would extend approximate 1/r dependence up to this diameter.

Finally, it seems inevitable that larger particles though highly shielded by smaller grains will receive more surface exposure than they would if grain contacts were made and broken in a random way, simply because intermediate size grains will fall off due to gravity rather than remaining to contribute to the shielding.

The main implications of the picture of grain surface exposure outlined above can be summarized as follows:

1. Very small grains less than about 10μm in diameter will show an exact 1/r dependence of the concentration of implanted or vapor deposited volatiles.
2. Grains up to the order of 50μm in diameter will show an approximate 1/r dependence.
3. Concentrations in larger grain-size fractions will tend to become independent of size even in the absence of true volume correlated components.
4. Large grains will be heavily shielded by smaller particles during most of their surface exposure.

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SOLAR WIND AND RELATED CORONAL VARIATIONS. A. J. Hundhausen, High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado 80307

In situ observations of the interplanetary plasma and magnetic field near the ecliptic plane have been performed on a fairly regular basis since the early 1960's. We can thus describe variations in the characteristics of the solar wind over the past sunspot cycle (cycle 20, 1964-1976) in considerable detail. On short time scales (hours to days) the fluctuations in solar wind flow parameters (e.g., speed, proton density, mass or energy flux density), composition, and magnetic field strength were dominated by well-known and organized patterns associated with "large-scale structure"--namely transient shock waves, thought to be produced by large solar flares, and slowly evolving streams and magnetic sectors that originate in coronal holes (1,2). The largest excursions of these parameters occurred in the shock waves; less extreme values occurred more in the more common streams.

Average values of solar wind properties over longer time scales (solar rotations to years) showed smaller changes related to the phase of the sunspot cycle. For example, the solar wind was most "intense", as measured by its speed or its mass or energy flux, in 1974, or just two years before sunspot minimum (3). This effect was clearly related to the development of a simple, stable pattern of two high-speed solar wind streams embedded in a pair of magnetic sectors. The solar origin of this pattern was a simple coronal structure with two large equatorward extensions of the semi-permanent "polar holes". The major changes in solar wind flow characteristics observed in the ecliptic plane during sunspot cycle 20 were thus related to the slow evolution of large-scale spatial structures in the corona, or ultimately to the evolution of the large-scale features in the solar magnetic field (3,2).

In contrast, it is difficult to ascribe any important changes in the long time-scale averages of solar wind flow characteristics to interplanetary shock waves and thus ultimately to solar flares and other transient activity. It appears that interplanetary shock waves occurred too rarely during cycle 20 to strongly influence the average state of the solar wind. Small changes in the composition of the plasma may, however, have been related to such events (4).

Study of the global pattern of coronal holes and the latitude variations in solar wind speed inferred from interplanetary radio scintillations shows that the solar wind variations observed in the ecliptic plane were part of a complex, three-dimensional, solar cycle evolution of the corona and interplanetary magnetic field. The polar regions of the sun, as reflected by the polar coronal holes and their equatorward extensions, seem to have played a crucial role in this evolution. This implies a more difficult problem than has sometimes been anticipated in relating the state of the solar wind, as directly observed or as inferred from indirect evidence, to the state of solar activity.

In the absence of direct observations of the solar wind from earlier sunspot cycles, any discussion of its properties and their variations must be based on indirect evidence--coronal, comet tail, cosmic ray, or geomagnetic data--and usually leads only to qualitative conclusions. For example, it is clear from eclipse photographs of the corona and from geomagnetic records that coronal holes with similar properties existed in earlier sunspot cycles and produced similar geomagnetic effects; this implies that similar solar wind streams were present. It is also clear, however, that the level of flare-associated geomagnetic activity has varied widely in different sunspot cycles. Our conclusion that flare-associated shock waves had little effect on the average state of the solar wind in cycle 20 is then of questionable applicability to other cycles. More detailed study of geomagnetic records leads to a similar

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variety of implications. While the familiar patterns of magnetic sectors can be traced back to the 1920's (5) substantial changes in the solar wind speed or magnetic field strength may have occurred since 1900 (6).

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EVIDENCE FOR SECULAR VARIATIONS IN SOLAR WIND COMPOSITION

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Implantation of solar wind ions into the surface of the moon leaves within lunar soil grains a record of the wind's composition. This record is partial and frequently disturbed but has the merit that it can extend back potentially to the dawn of the lunar regolith, i.e. about 4Gy ago. The duration of exposure of an individual sample to the solar wind may be adequately monitored by a number of observational parameters, including contents of the best retained solar wind species, e.g. N or Ar. Degree of such exposure is termed maturity. Determination of when a sample acquired its surface exposure is more difficult; a soil sample typically consists of many grains with widely varying exposure histories. For our purpose we require an estimate of the epoch when an average grain acquired its characteristic solar wind signature; we shall term this quantity the antiquity of a sample. No direct measure of antiquity has yet emerged but semi-quantitative estimates may be based upon products of cosmic-ray spallation, e.g. ^{15}N or ^{21}Ne, or upon contents of radiogenic nuclides, e.g. ^{40}Ar or ^{136}Xe, outgassed from the moon and reimplanted into the lunar surface. In addition, antiquity increases, albeit irregularly, with depth within core samples; however most data currently derive from surface soils. The antiquity of such samples will be represented by $^{40}Ar/^{36}Ar$ of their trapped gas. This measure is not absolutely calibrated, but a value of 2.5 appears approximately equivalent to a 3Gy antiquity (on an exponential decay curve).

Only eight solar wind elements have been isolated for study from lunar samples. We shall summarise the evidence for secular variations in amounts and isotopic compositions of these individual species. In general, the term "soil" will include microbreccias made by lithification of former soils.

Hydrogen The dominant constituent of the solar wind, H is heavily over-saturated in soils so that measured abundances yield no information about possible variations in the proportion of H to other elements. Isotopic measurements indicate that the solar wind contains no ^{2}D except for secondary spallation products [1].

Helium Like H, He is oversaturated so that variability in abundance does not necessarily connote corresponding variability in the solar wind, although it is known that He/H in the solar wind is highly variable on time scales of hours and years [2]. Also, the Apollo Solar Wind Composition experiment (SWC) measured variability in He/Ne on a time scale of years [3]. The SWC also revealed variations in $^{3}He/^{4}He$ between 4.08 and 5.38 x 10^{-4} within a 3y period [3]. This range is significantly above that found for trapped He in soils [4], suggestive of mass fractionation on the lunar surface. Amongst soils, $^{3}He/^{4}He$ does not vary systematically with maturity but does correlate inversely with $^{40}Ar/^{36}Ar$, suggesting a secular increase, by at least 23%, over a 3 to 4Gy period [5]. A possible contribution by reimplanted radiogenic ^{4}He is uncertain.

Neon Abundances of Ne in soils are variable, correlating with maturity, but $^{20}Ne/^{36}Ar$ systematically decreases with increasing maturity, suggestive of saturation by Ne, but with no evidence for short- or long-term variability of this ratio in the solar wind. The ratios $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ in soils are lower than those measured by SWC [3] in a trend consistent with mass fractionation, presumably on the lunar surface [6]. There is no systematic isotopic variation within Ne on the long term in soils or on the short term in SWC.

Argon Abundance of ^{36}Ar correlates very strongly with other reliable measures of maturity. Apart from the systematic decrease in parentless radiogenic ^{40}Ar during the life of the moon, there is no evidence for secular isotopic variability in trapped Ar.

Krypton The content of Kr correlates with maturity but its abundance relative to Xe in soils varies by a factor of three, the ratio $^{84}Kr/^{132}Xe$

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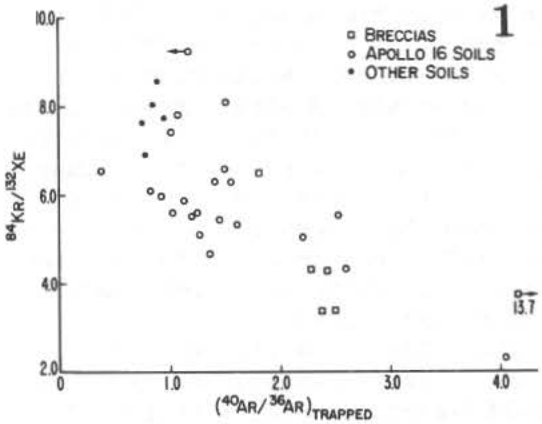

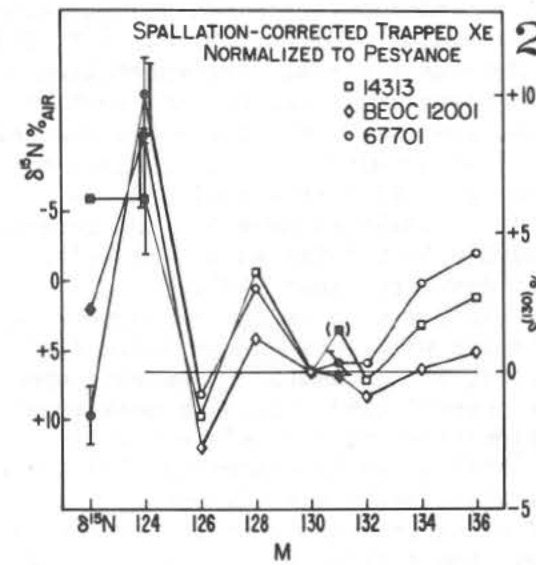

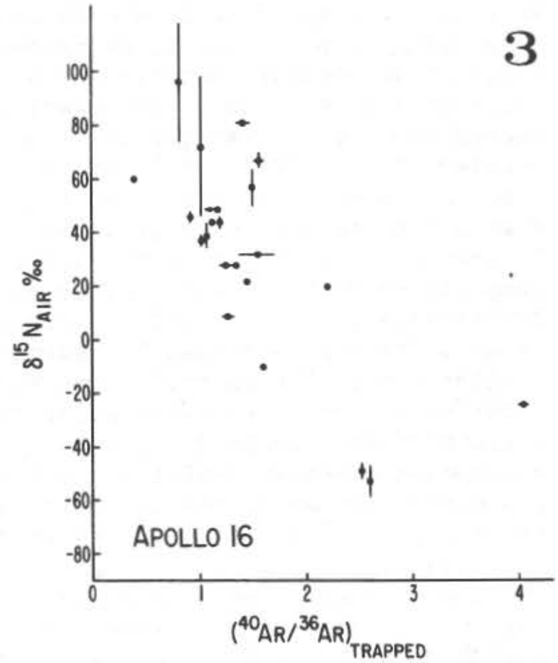

Fig.1: *The ratio* $^{84}Kr/^{132}Xe$ *decreases with increasing antiquity of exposure to the solar wind, monitored by* $^{40}Ar/^{36}Ar$.
Fig.2: *Xe isotopes with high n-capture cross sections (solid symbols) are not depleted in solar wind; decrease in their contents is not correlated with secular increase in* $\delta^{15}N$.
Fig.3: $\delta^{15}N$ *of trapped solar wind N decreases with increasing antiquity, indicating secular increase in* $^{15}N/^{14}N$.

being independent of maturity but decreasing systematically with antiquity, expressed either as ^{40}Ar/^{36}Ar, Fig.1, or as depth within Apollo 15 & 16 drill cores [7]. It is not clear whether this is due to change in Kr or in Xe. Isotopic composition of trapped Kr shows evidence for mass fractionation [8], not obviously related to maturity or antiquity, but whether this occurred on the moon or in the sun is not known.

Xenon The amount of Xe in individual soils correlates with maturity; the amount calculated for the regolith as a whole appears to be excessive for the current solar wind flux [5], suggesting a more intense solar wind the past, or possibly a secular decrease in the proportion of Xe in the wind (recall the systematic change in ^{84}Kr/^{132}Xe, above). Trapped Xe reveals isotopic evidence for mass fractionation [8,9], possibly resulting from lunar surface processes [9], and for occasional presence of parentless radiogenic ^{129}Xe and "fission" Xe [9,10]. The proportion of fission Xe,when present at all,increases with antiquity, as measured by ^{40}Ar/^{36}Ar. Those Xe isotopes characterised by high neutron capture cross sections, 124 and 131, are not perceptibly depleted relative to presumed primitive abundances, Fig.2, nor is there evidence for significant solar production of ^{128}Xe by neutron capture on ^{127}I [11]. These observations limit the neutron fluence experienced by the solar wind reservoir.

Nitrogen Abundance of N correlates very strongly with other measures of maturity [12] and these correlations may be used to constrain possible non-solar wind components to less than 5% of total N. Isotopic composition of N

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reveals a change of at least 30% during the life of the moon, with $^{15}N/^{14}N$ decreasing with antiquity, as measured by either ^{21}Ne [13] or $^{40}Ar/^{36}Ar$ [14], Fig.3. This secular increase in $^{15}N/^{14}N$ apparently cannot result from any known lunar process nor can it represent mixing of solar wind N with a hypothetical second component, whatever its source. It appears unlikely that preferential acceleration of ^{14}N or ^{15}N into the wind is responsible because the minimum proton flux required for N is less than that for the heavy noble gases which should therefore show large corresponding effects,but these are not observed. It seems, therefore, that the increase in $^{15}N/^{14}N$ represents a change in the composition of the solar wind reservoir [13]. This cannot be a simple mass fractionation because similar correlated fractionations are not observed in other solar wind species. Contamination of the solar convective zone by interstellar material putatively rich in ^{15}N is an unlikely explanation because such material entering the inner solar system would directly contaminate lunar N more profoundly than solar N. Also such material is unlikely to be ^{15}N-rich because asteration probably depletes the interstellar medium progressively in ^{15}N [15]. A nuclear process in the sun still appears the most plausible interpretation of the change in $^{15}N/^{14}N$ [13] despite serious observational constraints such as the very low nuclear γ ray flux from the sun, the low photospheric B abundance and the absence of neutron capture effects in solar wind Xe, Fig.2, [16]. Note that the solar wind data reveal no preference for the terrestrial $^{15}N/^{14}N$ ratio, $\delta^{15}N=0$ in Fig.3, so that this value is unlikely to have been of general significance in the solar system, despite having been inferred as the value for primitive N on Mars [17] and for present day N on Venus [18].

Carbon Regolith C contents correlate closely with maturity, suggesting that such C derives predominately from the solar wind. However,measured $\delta^{13}C$ values, which span a range of about 2%, exhibit no systematic dependence upon maturity, antiquity or obvious combinations thereof [19], although weak trends suggestive of exposure-dependent mass fractionation and a possible secular increase in $^{13}C/^{12}C$ related to increase in $^{15}N/^{14}N$ may be discerned [20].These trends are vague, however, and may not be statistically significant.

SUMMARY Of the analysable solar wind elements,only N reveals unequivocal evidence for a secular change in its isotopic composition [13], although the apparent increase in $^{3}He/^{4}He$ is probably also real [5]. The possibility of a secular decrease in the proportion of Xe in the solar wind may hint at a change in the coronal acceleration process as Xe has the highest minimum proton flux requirement of the well-retained solar wind elements [5]. However, it is unlikely that such a change could be responsible for the secular effect in N. The lack of other systematic trends in remaining elements serves as a serious constraint on possible mechanisms of isotopic evolution in solar wind N [16].

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TIME SCALES FOR THE PROTO-SUN AND PLANETS BASED ON EXTINCT NUCLIDES

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Two types of variations of isotopic abundances relative to the "cosmic" pattern ("anomalies") are intimately related to the formation of our solar system. The first type, caused by the lack of mixing between material from distinct pre-solar nucleosynthetic sources has been observed in more than ten elements. The other, which resulted from the decay of now-extinct radionuclides, has been found in four elements (Table 1). This paper is a tutorial summarizing the implication of extinct nuclides on the time scales for the collapse of proto-solar-clouds and for the accretion of planets from solid particles. Isotopic anomalies have been extensively reviewed (1-4) and references are too numerous to be cited individually.

It is convenient to discuss the implications of extinct nuclides in terms of a generic model of the nucleosynthetic history of solar system matter. In this model, elements were produced continuously for a period of T at a rate of $P \cdot \psi$ where P describes the production for each of the many sources and ψ is the birth rate of the sources. Additional production P' came from the late addition by the last source(s). Time interval Δ separates the continuous period and the late addition whereas Δ' is the interval between the late addition and the formation of the solar system. In such a model the ratio of an extinct isotope i of meanlife τ_i to a stable isotope j at the time of formation of the solar system is given by:

$$\frac{N_i}{N_j} \cong \frac{\langle P_i \rangle \psi(T)\, \tau_i \exp[-(\Delta + \Delta')/\tau_i] + P'_i \exp[-\Delta'/\tau_i] \ldots}{\langle P_j \rangle \int_0^T \psi(t)dt + P'_j} \quad (1)$$

where < > denotes average over many sources. With several extinct nuclides, eq. 1 may be used to determine Δ, Δ', and the factor D by which the late addition was diluted by production during period T (i.e., $D \equiv \langle P_j \rangle \int_0^T \psi dt / P'_j$), if the production ratios, ψ, and N_i/N_j can be estimated. Using the theory of nucleosynthesis, production ratios can be estimated (Table 1,2). In deriving these estimates the cosmic abundance pattern are usually used as constraints, so these ratios are valid only for products from "typical" sources for the solar system matter. Therefore, they may be reasonable approximations for the many sources in period T but could be grossly in error for the last source(s). ψ is believed to be a slowly varying function for the time scale ($\ll 10^9$ y) considered here and does not contribute much uncertainty. N_i/N_j has to be estimated from observed ratios in solar system objects. The N_i/N_j for the local solar system matter at the time of formation of the objects under study may be inferred from observation. However, the formation time for different objects may be different, and different locales of formation may have different isotopic composition due to spatial heterogeneity. Thus, for each nuclide there is a range of observed values as given in Table 1. For the analysis below we will use the "typical" values which are our best guess of the representative values.

Prior to recent discoveries of ^{26}Al and ^{107}Pd, it was well known that data for ^{129}I and ^{244}Pu could be explained with the above model with $\Delta \sim 10^8$y, $\Delta' = 0$, and $P' = 0$. This model underproduces ^{26}Al and ^{107}Pd by factors of $10^{4.6}$ and 10^3 (Table 1), respectively, implying that $P' \neq 0$. In this case Δ' can be estimated from ^{26}Al. If $\Delta \gg \tau_{26}$ then eq. 1 becomes

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$$N_{26}/N_{27} = (P'_{26}/P'_{27})/(D + 1) \cdot \exp(-\Delta'/\tau_{26}) \ldots \quad (2)$$

From (2) $\Delta' \lesssim 3 \times 10^6$y when $D \gtrsim 0$. The upper limit corresponds to the unlikely case where ^{27}Al in some carbonaceous meteorites came entirely from the last source. Clearly ^{26}Al requires a late addition almost at the instant of solar system formation. If Δ' for ^{107}Pd is also $\sim 10^6$y then $D_{110} \sim 10^4$ using eq.(2). So it seems that the last source contributed little material. If $D_{127} \sim D_{110}$ then the late addition would give $N_{129}/N_{127} \sim 10^{-4}$, close to the observed ratios. Therefore it is likely that most of the ^{129}I also came from the late addition rather than from the production $\sim 10^8$y earlier as was previously thought. However, similar analysis for ^{244}Pu gives $N_{244}/N_{238} \sim 10^{-4}$ indicating that most of the ^{244}Pu did not come from the last source but was produced in different sources which were active $\gtrsim 10^8$y ago. Although the above analysis did not provide a comprehensive model for all the extinct nuclides it revealed the following results: (i) There was nucleosynthetic activity almost at the instant of solidification in the solar system; (ii) This last activity contributed only a small fraction of the stable nuclides in the solar system; (iii) Nucleosynthesis seems to occur intermittently (at $\sim 10^6$y and $\gtrsim 10^8$y).

The late addition could be due to nuclear reactions in the early solar system. However, the pattern of isotopic anomalies for stable nuclides caused by nucleosynthetic heterogeneity is already suggestive of stellar sources. Therefore, it seems more plausible to attribute this last activity to a nearby pre-solar stellar source. This scenario is consistent with the formation of the proto-sun with other stars in an interstellar cloud. It is not yet clear whether the addition was before, during, or after the dynamical collapse of the proto-solar-cloud. If it was before the collapse, then the time interval between the initiation of the collapse to the formation of centimeter-sized solids (Ca-Al inclusions) in the solar system must be less than several million years. The exact limit depends critically on the value of the production ratio and the dilution factor which are not precisely known.

The ^{26}Al and ^{107}Pd results also provide an estimate of the accretion time scale. ^{107}Pd was discovered in iron meteorites which apparently crystallized from a melt in planetary interiors. The Pd data imply that the melt solidified within 2×10^6y. The time required to cool a planet is characterized by its heat diffusion time scale which is a function of the radius. Thus, the above cooling time implies that the parent body for those iron meteorites with ^{107}Pd had a radius $\lesssim 20$ km. For such a small body the most likely heat source is ^{26}Al decay. The melting of such a planet requires an $^{26}Al/^{27}Al \gtrsim 1.5 \times 10^{-5}$ if the elemental composition of the bulk planet is chondritic. The $^{26}Al/^{27}Al$ for Ca-Al inclusions in carbonaceous meteorites seems to have a typical $^{26}Al/^{27}Al$ of 5×10^{-5}. If this difference in $^{26}Al/^{27}Al$ reflects ^{26}Al decay with time then the time it took to accrete km-sized planets from cm-sized particles must have been less than 1.2×10^6y.

TABLE 1 EXTINCT NUCLIDES

Nuclide (ratio)	Mean Life ($\times 10^6$ y)	Abundance Ratio: Production^a	Old Model	Observed	Occurrence
$^{26}Al(/^{27}Al)$	1.0	$\sim 10^{-3}$	4×10^{-51}	$(0.5 - 100)5 \times 10^{-5}$	$\sim$ 10 Ca-Al inclusions
$^{107}Pd(/^{110}Pd)$	9.4	1.3	3×10^{-8}	$(2 - 4)\ 3 \times 10^{-5}$	2 iron meteorites
$^{129}I(.^{127}I)$	23	1.5	5×10^{-5}	$(0.7 - 1.7)1 \times 10^{-4}$	almost all meteorites
$^{244}Pu(/^{238}U)$	117	0.9	7×10^{-3}	$(0.5 - 8.7)1.5 \times 10^{-2}$	many meteorites

(a) Production ratio at a "typical" source for solar system material based on nucleosynthesis theory (5,6 and Appendix). (b) Model based on ^{129}I and ^{244}Pu only, calculated from eq. 1 with ψ = const., $P' = 0$, $T = 10^{10}$ y and $\Delta = 10^8$y. (c) Range and "typical" values observed in solar system objects.

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TABLE 2 ^{107}Pd PRODUCTION IN "COSMIC" r-PROCESS

		N^a	σ^b(mb)	$N_s{}^c$	$N_r{}^d$
(A)	^{104}Pd	0.143	197	$\equiv$0.143	$\equiv$ 0
	^{105}Pd	0.289	976	0.03	0.26
	^{106}Pd	0.355	150	0.19	0.16
	^{107}Pd	?	950	0.03	$\sim$0.2
	^{108}Pd	0.347	381	0.07	0.27^g
	^{110}Pd	0.154	$\equiv$ 0		$\equiv$0.15
			* * * * * * * *		
(B)	^{108}Pd	0.347^f	200^e	$0.193 \sim N(^{108}Pd) - N(^{110}Pd)$	
	^{107}Ag	0.231^f	1150^e	$0.034 \sim N_s(^{108}Pd)\sigma(^{108}Pd)/\sigma(^{107}Ag)$	
	^{107}Pd	$\sim N_r(^{107}Ag)$	=	$N(^{107}Ag) - N_s(^{107}Ag) \sim 0.2$	

(a) Cosmic abundance by number normalized to Si $\equiv 10^6$. (b) Theoretically estimated (n,γ) cross-sections (7). (c) s-process abundance obtained by assuming σN_s = constant for all isotopes. (d) r-process abundance $N_r = N - N_s$. (e) Measured (n,γ) cross-sections (8), error < 30%. (f) Carbonaceous meteoritic abundance for Ag (9) and Pd (10), consistent with the less precise solar photospheric value for Pd/Ag. (g) A better estimate might be $N_r(^{108}Pd) \approx N_r(^{110}Pd) = 0.15$.

APPENDIX: ESTIMATES OF THE ^{107}Pd/^{110}Pd PRODUCTION RATIO

In Table 2 two estimates of P_{107}/P_{110} are given for a "typical" source of the solar system r-process material. In the first method ^{107}Pd was interpolated from the solar system r-process contributions for the Pd isotopes, which are obtained by subtracting the s-process contributions from the "cosmic" abundance. The major uncertainty is the theoretical (n,γ) cross-sections which have typical accuracy of a factor of 2. Varying them within this limit we found that $P_{107}/P_{110} < 2.0$. We also believe that $P_{107}/P_{110} \gtrsim 1.0$ because of the decreasing trend of r-process abundance with mass in the Pd region. The alternative method is based on that the r-process contribution to ^{107}Ag must have all come through ^{107}Pd. This estimate involves only measured cross-sections but requires the elemental ratio Ag/Pd which is more uncertain than Pd isotopic ratios used above. By varying the Ag/Pd ratio within its uncertainty of ~ 1.5 we found $P_{107}/P_{110} \sim 1.3(-0.4 + 0.8)$. Thus, both methods gave $2.0 > P_{107}/P_{110} > 1.0$.

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ON KRYPTON ISOTOPIC ABUNDANCES IN THE SUN AND IN THE SOLAR WIND.

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Studies of the variations in solar-type gases in the solar system and in their isotopic abundances are expected to give information on (1) the composition of the source reservoir, the outermost region of the sun, (2) the mechanisms of acceleration of solar wind ions and (3) possible secular changes in the source reservoir due to nuclear reactions and fractionation mechanisms. Since the work on Pesyanoe xenon (Marti, 1969), our knowledge of solar-type gases has dramatically improved, mainly because of the study of solar wind samples returned by the Apollo missions. Pepin and Phinney (1979) and Geiss and Bochsler (1979) have recently analysed and reviewed the information.

The bulk of at least present day solar system gases is in the Sun. An understanding of solar system reservoirs and of the variety of isotopically distinct components observed in solar system matter, commonly termed "trapped", requires a detailed understanding of the composition of solar gas and of the mechanisms which may alter this composition during redistribution and trapping. Pepin and Phinney (1979) have discussed in detail the various xenon components and their interrelationships and list several important conclusions, based on their systematic analysis of solar-type xenon: There is no hard evidence for long-term temporal variation in solar wind xenon. Also, since there is no evidence for fractionation in Pesyanoe Xe, they argue against a solar source for the fractionation observed in the xenon isotope data from lunar fines.

The Kr data from a stepwise release of the noble gases in Pesyanoe revealed complex isotopic patterns, although the total Kr appears to be similar to that in the Kenna meteorite. Significant amounts of spallation Kr, due to the 43 m.y. exposure time to cosmic rays (Eberhardt et al., 1965), are expected to be present, especially in the highest temperature fraction. On the other hand, in contrast to the situation in xenology, fission components are not expected to make large relative contributions, because of the much lower fission yields in the Kr region and the larger trapped Kr concentrations. A repeat experiment on another Pesyanoe sample confirmed the isotopic structures in Kr and a measurement of ^{81}Kr in the 1500° fraction permits to calculate and correct the spallation component, based on known spallation systematics (Regnier et al., 1979) and exposure age. After this correction, a straightforward interpretation of the data suggests that "solar" Kr in Pesyanoe is a mixture of two components which, in a first approximation, appear to be mass fractionated in opposite directions, if compared to total rock Pesyanoe Kr (Figure 1).

Where did the fractionation take place, in the source reservoir, in the acceleration phase, during implantation of solar wind ions in Pesyanoe crystals or during gas release in the experiment? In order to gain more insight and to relate Pesyanoe Kr to that in the more recent solar wind, we prepared ilmenite separates from lunar fines 10084,29. Ilmenite appears to be a good choice from the point of view of low energy ion trapping characteristics (Eberhardt et al., 1972), but has the disadvantage of exhibiting large relative spallation Kr components, since Zr, as the major target element, is rather abundant. This problem was largely eliminated by preparing a sample of fine fines, 39-4B, the "sticky" residue, after processing ilmenite separate ,29-4A. Kr fractions released below 1000°C, including the largest fraction released at 900°C, do not reveal significant spallation components, except possibly at mass 78 and 80. The isotopic patterns below 900° is remarkably similar to those observed in Pesyanoe below 1000°, and, therefore, suggest themselves a normalization of one to the other. Table 1 shows that the low-temperature (L) fractions are, in fact, very similar, including any spallation excesses, if present. If these fractions could be taken to represent solar-

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type Kr, the congruency between the presumably ancient Pesyanoe-Kr and modern lunar ilmenite-Kr would argue against secular or long-term temporal variation in solar wind Kr. However, this close parallelism is not observed in the intermediate temperature (M) fractions. The Pesyanoe Kr released at 1000°C is of the L-type and, at this point, half of the Kr is released. The major release peak (44%) of lunar ilmenite-Kr (at 900°C), on the other hand, is clearly distinct from the L-type (Table 1), and approaches the composition of Kenna-Kr (Wilkening and Marti, 1976), if we allow for the presence of small ilmenite spallation excesses on masses 78 and 80 which clearly show up at higher temperature steps. One discrepancy remains at mass 86. This M-type composition is missing in Pesyanoe. An analysis of the high temperature (H) release is complicated by the fact that spallation components become more prominent, particularly in the ilmenite-1600° fraction. Fortunately, our present knowledge of spallation Kr systematics in lunar ilmenites is quite good (Regnier et al., 1979). Spallation-corrected H-components are again remarkably similar in Pesyanoe and lunar ilmenite. Because of the result that Pesyanoe-total conforms to the Kenna pattern, the H-component, as the other half of Pesyanoe-Kr, must be complementary to L-type, fractionated favoring the heavy isotopes. This is also true for lmenite-H, except that, in terms of concentrations, H is more abundant than L and, therefore, the ilmenite-total cannot match the Pesyanoe total exactly.

The question of origin of these L, M and H structures is intriguing. Diffusion processes allow for early and terminal mass fractionated structures, but predict a broad intermediate range. Although the M composition is observed in lunar ilmenite (but only 44%), it appears to be missing from Pesyanoe. If L and H are distinct components, how do they relate to each other and to the Sun? Do they reflect different solar wind energy spectra and, therefore, varying depth of implantation, or is the more tightly held component due to redistribution effects? As in the case of Pesyanoe (Marti, 1969), the xenon in lunar ilmenite 10084,29-4B, as observed in the individual temperature steps, is remarkably constant, except for small and variable spallation and fission effects. On the other hand, $^{36}Ar/^{38}Ar$ ratios appear to follow the trend seen in the Kr data, in the case of lunar ilmenite, but not in Pesyanoe. It is possible that the presence of spallation Ar might mask the effect, but it is interesting to note that there is a marked dip in the release curve of ^{36}Ar at 1000° (but not ^{40}Ar). These constraints still permit a number of model interpretations and some of those will be considered.

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On Krypton Isotopic Abundances in the Sun and in the Solar Wind.

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Table 1. "SOLAR"-TYPE KR: LUNAR ILMENITE(10084,29-4B) VS. PESYANOE

SAMPLE RATIO*		78	80	82	83	84	86
ILMEN.-600°/PESY.-600°		1.008	.995	1.0000	.9999	1.0028	1.0037
	±	.017	.016	.0000	.0049	.0072	.0051
ILMEN.-800°/PESY.-1000°		.995	.994	1.0000	.9978	1.0038	.9993
	±	.017	.014	.0000	.0060	.0059	.0053
ILMEN.-900°/PESY.-1000°		.986	.9903	1.0000	1.0036	1.0080	1.0127
	±	.017	.0083	.0000	.0043	.0056	.0039
ILMEN.(600+800)/PESY.(600+1000)		1.001	.9940	1.0000	.9983	1.0033	1.0002
ILMEN.-900°/Kenna		1.046	1.0155	1.0000	1.0006	.9979	.9896
	±	21	74		36	30	34

*Ratio of normalized (^{82}Kr = 1.000) isotopic compositions.

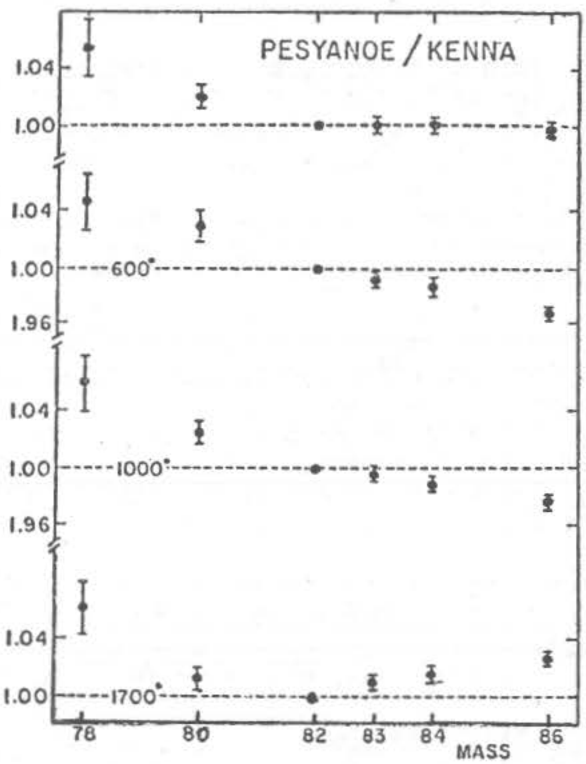

Figure 1. The normalized (^{82}Kr = 1.000) isotopic abundances observed in Pesyanoe-3 (total) and in three temperature fractions thereof, are compared to those in Kenna (Wilkening and Marti, 1976). (For an identical composition, the ratios are = 1.000.)

SPACECRAFT MEASUREMENTS OF THE ELEMENTAL AND ISOTOPIC COMPOSITION OF SOLAR ENERGETIC PARTICLES, R. A. Mewaldt, Caltech 220-47, Pasadena, CA 91125.

Solar flare events frequently inject large fluxes of heavy nuclei into the interplanetary medium with energies $\gtrsim 1$ MeV/nucleon. Spacecraft measurements of the elemental and isotopic composition of these nuclei may provide a direct measure of the present solar elemental and isotopic makeup, providing crucial information for understanding the history of solar system material. In addition, such observations are particularly useful for interpreting the integrated effects of solar contributions to other solar system reservoirs. Finally elemental and isotopic measurements add new dimensions to the study of the systematics of solar flare acceleration. This paper will review recent progress in the observation and interpretation of solar flare elemental and isotopic abundances.

Our knowledge of the elemental composition of solar flare nuclei with $1 \leqslant E \leqslant 100$ MeV/nucleon has been improved significantly in the past few years by the development of improved spacecraft instrumentation, coupled with the onset of increased solar activity in 1977. The relative abundances of the majority of elements with $1 \leq Z \leq 28$, including relatively rare elements such as Na, Al, Ar, Ca, Cr, and Ni, have now been measured in a number of large flares[1]. When normalized to oxygen, the solar particle abundances are enhanced relative to solar atmospheric or meteoritic abundances by a factor $Q(Z)$ which depends on the nuclear charge Z, and varies from flare to flare. For example, Q for Fe nuclei at ~ 10 MeV/nucleon varies from ~ 1 to ~ 20. The detailed dependence of Q on Z shows an interesting correlation with first ionization potential[1], similar to that found for the galactic cosmic ray source abundances[2]. Indeed, "average" abundances of heavy nuclei in solar flares are remarkably consistent with those deduced for the galactic cosmic ray source.

Within the past year the first isotope measurements of solar flare nuclei heavier than helium were reported. Among the elements whose isotopic composition has been measured to date, neon is of particular interest in that the solar flare $^{20}Ne/^{22}Ne$ ratio[3,4] is significantly different from that observed in the solar wind, but consistent with that for the meteoritic component neon-A[5]. It therefore appears that the Sun is capable of emitting two distinct isotopic components at different energies, and that isotopic fractionation may be taking place in either the solar wind or solar flare acceleration mechanisms.

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5) see, e.g., Podosek, F.A., Ann. Rev. Astr. Ap., 16, 293, 1978.

MECHANISMS OF SOLAR VARIABILITY ON TIME SCALES OF 10^5 TO 10^9 YEARS.

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The question to be addressed is what mechanisms operate on the sun with characteristic time scales of 10^5 to 10^9 years and how do these influence the outputs of radiation, solar wind plasma, magnetic fields, and energetic particles. We should also add to the list of outputs the modulation of galactic cosmic rays, since this "input" into the inner solar system comprises an important index of past solar activity. Some aspects of the main question, such as the evolutionary change of solar luminosity, can be answered with considerable assurance by well accepted models of the sun. Others, such as the level which solar magnetic activity attained in the past, are completely beyond the scope of current theory. As each mechanism and timescale is examined, we shall indicate how securely we can depend upon the conclusions regarding its influence on the solar outputs.

The initial appearance of the sun occurred when material in a gravitationally collapsing gaseous cloud became sufficiently hot due to adiabatic compression to become luminous. During this so called Hayashi phase (1) the sun's radius decreased rapidly as the surface temperature gradually rose and the total luminosity actually decreased. Since we know nothing about the operation of the solar magnetic dynamo in such a protostar, we can say nothing about solar activity during this stage. However, from the very fact that the protosun must have gotten rid of a large amount of angular momentum to have arrived at its current low rotation rate, we can presume that the solar wind - the only effective rotational brake - must have been considerably stronger during this stage. The Hayashi stage of the sun ended after about 10^7 years when the central temperature reached $\sim 10^7\,^{\circ}K$ and hydrogen burning was ignited.

The hydrogen burning or main sequence stage of the sun has an overall lifetime of $\sim 10^{10}$ years and is dominated by the slow increase in its luminosity (2) (3) according to

$$\frac{dL}{L} \sim \text{const.}$$

The principal mechanism causing this increase in luminosity is the accumulation of ^4He, the "ashes" of hydrogen burning. This conclusion as derived from the "standard models", models which were initially chemically homogeneous with elemental abundances of the photosphere and without internal mixing, suggests that the sun 4.7×10^9 yr BP had a luminosity only $\sim 70\%$ of the current value. Models for the climate of the current terrestial atmosphere predict that such a low solar flux would have resulted in irreversible global gaciation (4). The absence of such glaciation and the observed low neutrino flux cause us to re-examine the applicability of the "standard" models to solar evolution. A detailed examination of the available astronomical evidence indicates that the overall conclusions of the "standard" models are robust - tinkering within credible limits can change the overall behavior of the sun only within bounds $\sim 10\%$ in luminosity (5). (The lack of early global gaciation of the earth is to be attributed to a primative atmosphere rich in infrared opaque gases.) Both theory and the observation of other stars like the sun suggest that chromospheric and, coronal activity (i.e. solar wind flux) decay slowly during the main sequence evolution. However, both were probably within $\sim 2X$ of the current values by 3.5×10^9 years BP.

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MECHANISMS OF SOLAR VARIABILITY

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In the range of timescales from 10^5 to 10^9 years episodic changes in the sun may also have occurred with relatively large ($\sim$30%) changes in radiative flux, neutrino flux, and presumably solar wind flux. The mechanism for one such fluctuation - The Solar Spoon (6) - depends upon the accumulation of partly burned solar fuel (^3He) at a zone at about $0.25R_{\odot}$ from the center. After about 3×10^8 years the accumulated ^3He causes the interior to be unstable to gravity mode oscillations; and it is hypothesized that these can lead to mixing of this partly burned fuel into the interior. The introduction of fresh fuel into the core causes a transient response of the sun which lasts $\sim4\times10^6$ years and which recurrs every $\sim3\times10^8$ yrs. One explanation of the low neutrino flux is that the sun is still recovering from such an episode. It is tempting to identify the $\sim10^8$ years between major geological epochs as a solar forcing of terrestial climate (7).

At shorter time scales, the basic process which might lead to oscillations in solar output lie in the convection zone. One process which <u>might</u> be operating on the sun is an interaction between the efficiency of convection and the magnetic field. Since the interaction between rotation and convection is responsible for the existance of the field, the possibility exists for a non-linear feedback between the field and convective efficiency. Unfortunately, the characteristic time for such an oscillation depends upon the unknown details of the interaction. At present even such a fundamental answer as whether the field increases or decreases convective efficiency is unknown. Models (8) have demonstrated, however, that solar luminosity responds sensitively to the efficiency of convection and that the sun has a relaxation time $\gtrsim10^5$ yr for perturbations of this type.

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RARE GASES IN THE MODERN AND ANCIENT SOLAR WIND: ELEMENTAL ABUNDANCES, FLUXES, AND ISOTOPIC COMPOSITIONS. R. O. Pepin, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

Elemental abundances. Spacecraft measurements of the elemental abundance ratios He/H, O/H, Si/H and Fe/H in the modern solar wind, and measurements of Ne/He and Ar/He directly implanted by the wind into foils exposed on the lunar surface during the Apollo missions, agree within error with determinations of the relative abundances of these elements in the solar surface and corona, and with estimates of average solar system abundances(1,2). No direct measurements exist of elemental abundances of the heavy rare gases Kr and Xe in either the sun or the solar wind, but the absence of mass-dependent deviations of solar wind relative to solar abundances for elements through iron argues that ion fractionation in acceleration from the solar wind source region does not occur to any great extent for heavier ions, and that Kr and Xe abundances in the wind are probably representative of the solar surface within a factor $\sim$ 2-3. We can estimate what these abundances are in two ways. (a) Cameron's(3) tabulation of average solar system elemental abundances, relative to H, are in good agreement with solar surface/corona and solar wind relative abundance measurements through Fe(1,2). If this agreement extends to heavier nuclei, the solar wind Xe/H ratio is $\simeq 1.7 \times 10^{-10}$(3). (b) Solar wind ions are implanted to depths of $\sim 10^{-5}$ cm in materials exposed on the lunar surface. Diffusive and other losses of He, Ne, and possibly Ar from most minerals occur in the lunar environment, but one mineral -ilmenite- is particularly retentive of implanted solar wind gases (except for He) and has been shown to contain Ne and Ar in approximately the solar wind ratio(4). If the relative abundances of the heavier gases in 12001 ilmenite(4) are also representative of the solar wind, then the solar wind Xe/H ratio is readily calculated from data in references (1,2,4) to be $\simeq 8.9 \times 10^{-10}$, a factor $\sim$ 5 higher than that calculated above from estimates of average solar system abundances. This is probably an upper limit, because ilmenite and other minerals may selectively retrap Xe relative to lighter species from ambient solar wind gas clouds mobilized from lunar surface materials by impact and solar heating, and because Xe in the lunar regolith does contain an indigenous lunar component unrelated to the solar wind. The indigenous Xe, however, amounts to a relatively small fraction of the total: < 20%(2) and probably much less(5). It is important to note that the $(Xe/H)_{SW}$ ratio inferred above from gases implanted in lunar ilmenite refers not to the modern solar wind but primarily to the ancient wind: the Ne, Ar, Kr and Xe in 12001 ilmenite were trapped during episodes of exposure at the top of the regolith which began $\sim$ 3.3 billion years ago and continued, at unknown times and with unknown durations, until the sample was collected on the surface by Apollo 12.

Fluxes. A calculation carried out by Geiss(1) suggests that the flux of solar wind ions intercepted by the moon may have been higher in the past than it is today. Three deep ($\sim$ 3m) drill core samples of the upper lunar regolith were recovered by the Apollo 15, 16 and 17 crews. Except for a layer in the upper part of the 17 core which was apparently deposited relatively recently by ejection from a nearby impact crater, the soil in all three contains high abundances of solar wind implanted rare gases from top to bottom. The average concentration of trapped ^{132}Xe atoms down the 240cm length of the 15 core, for example, is $\sim 4.7 \times 10^{11}$ atoms/g, amounting to $\sim 7.4 \times 10^{14}$ total Xe atoms/cm^2 column(1). With the modern solar wind H flux of 2.7×10^8/cm^2-sec, and taking $(Xe/H)_{SW} \simeq 1.7 \times 10^{-10}$ as given above for a solar wind composition which follows Cameron's(3) average solar system abundances without fractionation, Geiss, assuming no Xe loss from the moon and taking into account periodic shielding caused by lunar rotation and by the moon's immersion in the tail of the earth's geomagnetic cavity, calculated

Rare Gases in the Solar Wind

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a solar wind irradiation period of $\sim 2.6 \times 10^9$ years for the regolith just to the depth sampled by the core(1). But the average regolith thickness at the 15 site is a factor ~ 2 greater than the core penetration depth(6), and if the unsampled section is likewise characterized by high concentrations of solar wind species then the total irradiation time required at the present flux exceeds the Apollo 15 site age of $\sim 3.3 \times 10^9$ years. The discrepancy is increased if some solar wind gases have been lost from the moon by sputtering, intense impact, or acceleration by the local electric field(7). A higher solar wind flux in the past would seem to be required(1). Similar conclusions may be drawn for Apollo 16 (1) and Apollo 17, although in the latter case much of the regolith may have accumulated by lateral transport into this valley-floor site. If so, the argument above, which requires no net accumulation or erosion of the regolith at the drill core locations by lateral transport, is invalid.

If the $(Xe/H)_{SW}$ ratio over the past few billion years has been near the upper limit of $\sim 8.9 \times 10^{-10}$ estimated above from trapped solar wind rare gases in 12001 ilmenite, rather than the value deduced from estimates of average solar system abundances, then the necessity for invoking a higher solar wind flux in the past to account for a high gas loading of dust grains throughout the thickness of the lunar regolith disappears *unless* losses of solar wind gases from the moon have been relatively massive. On the other hand, theoretical considerations of the mechanism of ion acceleration from the solar wind source region, and experimental results on He and Ar abundances in the solar wind collection foils deployed on the lunar surface, suggest that Xe may be *depleted* in the wind relative to its solar abundance -although by no more than a factor 3(1,2). If it is, and if Cameron's (Xe/H) ratio(3) is approximately valid for the sun, then the relative abundance of Xe in lunar ilmenite is not a good measure of the solar wind, and by Geiss's argument the solar wind flux must have been higher in the past by a large factor. At the moment, the question is open.

Isotopic compositions. Of all rare gases measured in lunar samples, and in "gas-rich" meteorite materials exposed to the solar wind in the distant past, only He shows clear evidence for a secular variation in solar wind (and probably solar) isotopic composition. $(^4He/^3He)_{SW}$, as preserved in ilmenite grains from the interior of an old lunar soil breccia (soil cemented by impact), and thus protected from exposure to the more recent solar wind, is $\sim 15\%$ higher than in ilmenite from unconsolidated soils; in some meteorites that were probably irradiated by the wind ~ 3.5 - 4.5 billion years ago, this ratio is almost 50% higher(4).

In general, isotopic variations seen in trapped solar wind Ar and Kr in lunar and meteoritic samples seem to be consistent with mass fractionation during diffusive gas loss in their local environments, and/or with the addition of non-solar-wind indigenous gases. This may not be the case for Ne. $^{20}Ne/^{22}Ne = 12.9$ in 12001 ilmenite is $\sim 6\%$ lower than the average solar wind value of 13.7 (1,4). Diffusion of Ne from the ilmenite is probably *not* responsible for the reduction because the Ne/Ar ratio in this sample agrees with the solar wind value and thus implies negligible diffusive loss. While ion trapping and/or saturation effects could be responsible(4), it is interesting to note that the Ne isotopic data given by Eberhardt *et al.*(4) nominally show the same time trend as for He: a progressive enrichment of the heaviest isotope, compared to the modern solar wind, in lunar and meteorite samples containing progressively older solar wind. There may therefore be a secular variation in the isotopic composition of solar wind Ne as there is in He, with the ancient wind isotopically heavier for both elements.

Trapped Xe in the lunar fines and breccias is isotopically complex. Its composition is variable, with indications of a sample age dependency, and generally does not agree with that of Xe in the Pesyanoe meteorite, which is considered to be a measure of ancient solar wind Xe composition(8). However, a recent model of lunar trapped Xe compositions shows that they can be adequately explained by mass fractionation (in lunar surface processes) of a time-independent base composition plus addition of Xe generated by spontaneous fission of U and Pu in the lunar interior, with both the magnitude of the fractionation and the relative abundance of the superimposed fission Xe increasing toward the past in the interval 3 - 4 billion years(5). The time-independent base component is identified as the primary solar wind Xe originally implanted at the surface of the regolith. Its isotopic composition, yielded by the model, is in excellent agreement with that of the abundant Xe of presumed solar wind origin in Pesyanoe(5). So we know the composition of ancient solar wind Xe, and know it to be approximately constant over the interval ∿ 3 - 4.5 billion years ago.

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^{10}Be IN POLAR ICE CORES AS A RECORD OF SOLAR ACTIVITY

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The intensity of primary and secondary cosmic rays in the earth's atmosphere is anticorrelated with solar activity, as measured by the 11(or 22) year sunspot cycle. Cosmogenic nuclide production, which is directly proportional to this intensity, is therefore also inversely correlated to solar activity (1). By studying concentration profiles of these cosmogenic nuclides in appropriate geophysical reservoirs, we may thus hope to obtain evidence about solar activity in the past.

The most favourable cosmogenic species for such studies appears to be ^{10}Be (half life 1.5 x 10^6 years). Because it is along with ^{14}C, the only long lived nuclide formed from nuclear reactions on oxygen and nitrogen, the principal components of the atmosphere, it is the second most abundant cosmogenic isotope. Unlike ^{14}C, it is rapidly ($\sim$ 1 year) precipitated to the earth's surface, and thus its deposition rate will respond rapidly and sensitively to changes in production rate.

Until recently, detailed investigations with ^{10}Be were precluded by its very low level of radioactivity. However we have recently developed an accelerator technique (2) which presently allows us to detect as few as 10^7 atoms of ^{10}Be, thus making measurements of the type discussed below feasible.

The ideal geophysical reservoir in which to study ^{10}Be variations due to solar modulation should have the following characteristics : i) continuous record ii) good time resolution iii) an independent and reliable chronology iv) minimum interference from other effects which could cause cosmogenic production variations. The above considerations have led us to conclude (tentatively), that the most favourable reservoirs for finding a record of solar influence on ^{10}Be should be polar ice cores. Such cores contain a continuous, undisturbed record of ^{10}Be in precipitation dating back at least 10^5 years. With the sensitivity that we have already achieved with the cyclotron, we can have time resolution as fine as one month in currently available ice cores. Thus, in addition to being able to look for variations in the envelope of the solar cycle (ie Maunder minimum (3) type variations) it should be possible to investigate whether the 11 year cycle itself was operating during such times.

Methods used thus far to establish a chronology for polar cores include stable isotope variations, ice flow models, climatic horizons and extrapolation from well established precipitation rates near the surface. While these procedures appear to give a self consistant picture, there is clearly a need for a detailed and reliable technique if one is to attribute ^{10}Be concentration variations to production variations. One possibility for the future is to take advantage of the greatly increased sensitivity of the accelerator technique to measure ^{14}C in the ice cores (because of the large "damping" effect, ^{14}C concentration in the atmosphere responds relatively slowly to production variations). Another possibility, that we are currently exploring is to use seasonal variations of ^{10}Be concentration in precipitation (4) to distinguish yearly accumulation rates.

^{10}Be IN POLAR ICE CORES AS A RECORD OF SOLAR ACTIVITY

G. RAISBECK, F. YIOU

The most serious problem with interpreting ^{10}Be variations as being due to solar modulation is the fact that other effects - in particular variations is the geomagnetic field intensity - can also lead to variations in cosmogenic production rates (1). For some situations (such as the 11 year cycle) the time scale should be sufficiently characteristic so as to preclude ambiguity. In the case of longer term variations one can hope to exploit differences in the geographical regions where the two mechanisms predominate. The geomagnetic effects are most pronounced in the equatorial regions, and minimal near the poles. Thus cosmogenic isotopes formed in the troposphere (which tend to deposit locally) will be dominated by geomagnetic variations near the equator, and by solar modulation, near the poles. In the stratosphere a much greater mixing occurs. Thus when stratospheric produced ^{10}Be is deposited at the earth's surface, the latitude production dependence is largely lost, and in instead replaced by a pattern characteristic of stratospheric - troposheric exchange. Here again the polar regions find themselves in a favourable situation because it is generally believed that there is a minimum of stratospheric "fallout" at high latitudes (1).

From the above discussion, it is evident that polar ice cores should be the most favourable reservoirs for finding ^{10}Be variations due to solar modulation, while sediments from mid-latitude lakes and inland seas should be the most sensitive to the paleomagnetic variations. A comparison of ^{10}Be variations in these reservoirs may provide a means of distinguishing between the two effects.

In order to get some quantitative idea of the expected variation of ^{10}Be in polar cores due to solar mudulation, we have recently looked at the concentration of ^{7}Be in ground level air samples (which are largely tropospheric in origin) collected in France, as a function of the Zurich sunspot number (5). The results, which are shown in Fig.1, suggest that one might expect a variation of $\gtrsim$ 30% in ^{10}Be at the poles. Such a variation would be readily measurable by the procedure we have described.

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^{10}Be IN POLAR ICE CORES AS A RECORD OF SOLAR ACTIVITY

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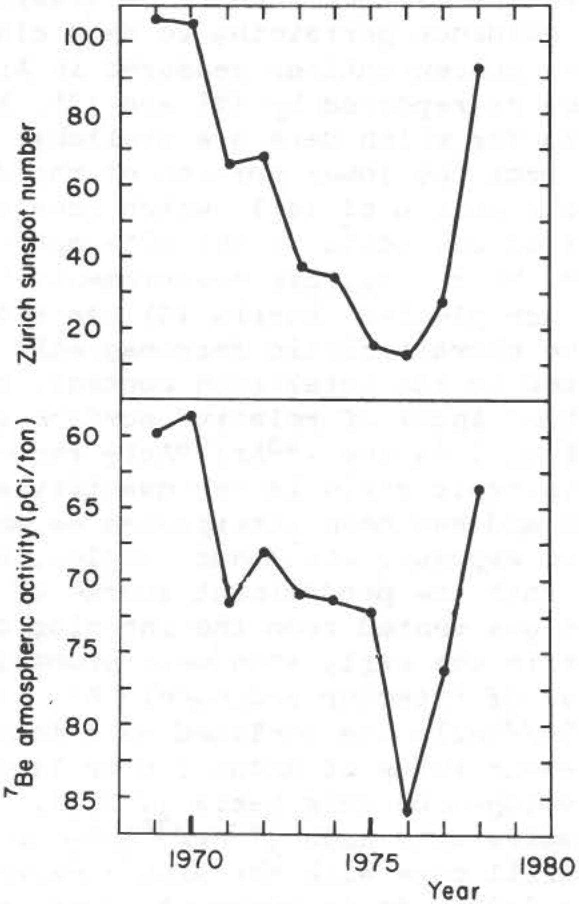

Fig. 1 -

Yearly mean Zurich sunspot number for 1969-1978 (above)
Yearly average ^{7}Be concentration in air samples at four locations in France for 1969-1978. (Note inverted scale, to facilate comparison with sunspot number). (below)

THE HISTORY OF SOLAR WIND INTENSITY AS RECORDED IN APOLLO 16 SAMPLES. J. Ray and D. Heymann, Rice University, Houston, Texas 77001.

Geiss (1) has stated that "it is difficult to escape the conclusion that the average solar wind (SW) flux during the last several billion years was larger than it is today." Herein we critically examine evidence pertaining to this claim. In Fig. 1 we have plotted ^{36}Ar concentrations measured in Apollo 16 soils versus I_s/FeO values as reported by (2) and (3). All surface and near surface samples for which data are available have been used. In addition, soils from the lower portion of the deep drill core (the modal petrologic unit A of (4)), which have the highest $(^{40}Ar/^{36}Ar)_T$ values of any soils at the site apart from fines 61221, are included. Where multiple measurements have been reported, average values are plotted. Morris (5) has shown that I_s/FeO, the intensity of the characteristic ferromagnetic resonance of a lunar soil normalized to its total iron content, can be used as a "generally applicable" index of relative surface exposure age. Also indicated in Fig. 1 is the $(^{40}Ar/^{36}Ar)_T$ range for each sample. This trapped isotopic ratio is the quantity after correction for radiogenic ^{40}Ar and has been interpreted as an indicator of the epoch of surface exposure for lunar samples. Heymann and Yaniv (6) proposed that the predominant source of trapped lunar ^{40}Ar is reimplanted gas vented from the interior of the moon. As geologic conditions in the early moon were probably more favorable for the release of interior radiogenic Ar, it is thought that the ratio $(^{40}Ar/^{36}Ar)_T$ has declined as a function of geologic time to its present value of about 1.0 or less. A rough chronology has been developed on this basis (7,8,9).

All of the samples with high $(^{40}Ar/^{36}Ar)_T$ in Fig. 1 are from MPU-A in the deep drill core with the single exception of the very immature fines 61221. As is apparent, these soils are systematically more gas-rich than soils with lower trapped Ar ratios. (A least-squares fit to the North Ray crater soils has been drawn in. Samples collected on the ejecta blanket of this 50×10^6yr old crater are thought to have received the bulk of their trapped gases since that time. Note that any such growth curve is constrained to pass very near the origin since the production of spallation ^{36}Ar via cosmic rays, which can take place at regolith depths below the upper 1 mm where I_s fine-grained metal is formed, amounts to only about 0.03×10^{-4} cm^3 STP/g over 4.5×10^9yr.) If the relationship between a unit of the I_s/FeO scale and the corresponding surface residence time has remained constant over the history of the lunar regolith, or equivalently, if the micrometeorite flux has remained unchanged, then the foregoing statement is assured. However, if the micrometeorite flux were greater several billion years ago than now, then the index I_s/FeO has overestimated the surface ages and the gas accumulation rates for soils with high $(^{40}Ar/^{36}Ar)_T$ are underestimated. In short, then, Fig. 1 appears to support the claim for a greater SW flux several billion years ago provided that the micrometeorite flux was not much different at that time and assuming the particle trapping efficiency of lunar material for SW rare gases has not changed.

Because the inert gases are implanted and retained with something less than 100% efficiency, we have examined nitrogen data for the Apollo 16 soils to clarify the matter of retention effects (Fig. 2). The chemical activity of N permits this element to be far better retained than is Ar (10,11). Unfortunately, N measurements for the deep drill core are very limited. Only two data points in Fig. 2 have $(^{40}Ar/^{36}Ar)_T$ in excess of 3.0: soil 61221 and a mixed sample from 60002 at the top of MPU-A (12). Despite this paucity of information, the clear implication of Fig. 2 is for a near linear covariance of [N] and I_s/FeO independent of epoch of exposure. Such an eventuality should occur if [N] and I_s/FeO growth rates have remained constant over the past $\sim 4\times10^9$yr or if both have varied coherently over the same interval. Case I. In the former instance, Fig. 1 requires a higher rate for trapping inert gases in the past despite the constancy of N implantation. We interpret this combination of trapped N and Ar data to indicate that, while the SW flux remained constant, the average bulk SW velocity (and, hence, implantation energy) was higher--implying a lower SW number density. In this way, the record for retentive N was unaffected while Ar experienced a higher retentivity due to deeper implantation depths. Case II. Alternatively, we have proposed elsewhere (13) that the secular increase in lunar trapped $^{15}N/^{14}N$ ratio may be understood by accretion onto the solar surface of N-enriched planetary nebula material. This would mean that, for constant average SW mass flux, the N flux at the moon would have declined with time. Fig. 2 is compatible with this possibility only if the micrometeorite flux was also greater and if the time constants for the two unrelated processes are similar. Data in Fig. 1 would then require that the trapping efficiency for Ar was even larger than in Case I and again this is likely to be due to a greater SW velocity in the past. We do not regard this possibility as any less reasonable than Case I despite the apparently fortuitous correspondence of [N] and micrometeorite variations required. Case III. If the SW and micrometeorite fluxes were both higher but by amounts consistent with Fig. 2, the Fig. 1 still necessitates a factor responsible for the apparent excess abundance of ancient Ar. Once more, this is consistent with a larger SW velocity in the past. In any event, a greater SW velocity several billion years ago is probable. On the other hand, a larger SW flux is consistent with the data only if the micrometeorite flux was also greater in such a way that the [N] versus I_s/FeO relationship has remained essentially unaffected. The magnitude of the velocity change cannot be assessed at present.

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Figure 2

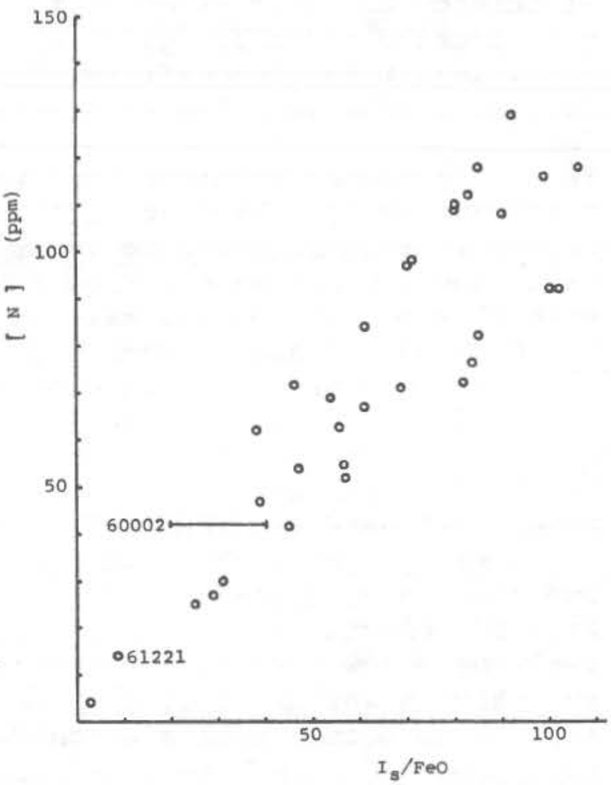
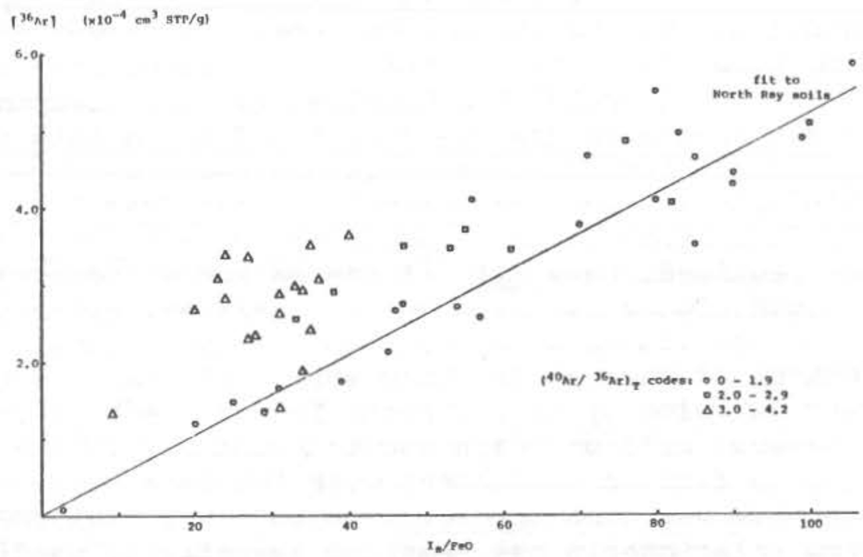


Figure 1



A MODEL FOR NITROGEN ISOTOPIC VARIATIONS IN THE LUNAR REGOLITH. J. Ray and D. Heymann, Rice University, Houston, Texas.

Introduction. Investigations by (1,2,3) have established that the isotopes of nitrogen implanted into lunar soils have undergone a long-term secular change. Kerridge et al. (4) have reviewed various mechanisms for effecting the necessary increase in $^{15}N/^{14}N$ with geologic time as required by observation. They conclude that data from regolith samples are consistent with the hypothesis that this change has occurred in the solar convective zone (SCZ) rather than evolutionary processes on the lunar surface but that current models are incapable of satisfactorily accounting for such a change. We consider here a variant of an idea proposed elsewhere, that of "contaminating" the SCZ.

Observational evidence favoring an increase in the $^{15}N/^{14}N$ ratio over lunar history will not be repeated here; reference is instead made to the review of (4). The salient points, however, include the following: a. Variations in N isotopic compositions are found, expressed as the per mil deviation from an air standard, δ^{15}, which range from -190‰ (5) to +120‰ (6), the presumed present-day solar wind (SW) value. b. Study of the breccia 14318, which has a well-defined formation age of 3.7×10^9yr (7), suggests that N trapped at or prior to that time is characterized by bulk $\delta^{15} \sim -60$‰ (3). c. While (3) note the possibility exists that "the change from very light to very heavy nitrogen implantation occurred over most of the history of the moon," observations do not seem to exclude a step-function type of change (6). Data for the Apollo 16 soils, however, argue strongly for the former case as can be seen in a plot (not shown) of δ^{15} versus $(^{40}Ar/^{36}Ar)_T$.

Solar accretion. We propose that a solar surface contamination occurred during the first half-billion years of the solar system due to passage through a single dense cloud with very low $^{15}N/^{14}N$. Gradual assimilation of primordial solar material into the affected convective zone from below would slowly restore the isotopic balance to its original complexion. Models have been developed for the accretion of ISM material onto stellar surfaces (8) and into planetary atmospheres (9). But these studies have been directed toward the problem of assessing the cumulative impact due to statistically probable random cloud passages.

Assuming the SCZ maintains a constant total mass, despite SW loss, by bringing up material from below, then its isotopic composition as a function of time can be described by

$$\delta^{15}_{scz}(t) = \delta^{15}_{\odot} - \left[\delta^{15}_{\odot} - \delta^{15}_{scz}(0)\right] \exp\left(-F_{sw}\, t / \Delta M_{scz}\right)$$

where $\delta^{15}_{\odot}$ is the composition of the sun immediately below the SCZ, F_{sw} is the mass loss rate due to the SW and ΔM_{scz} is the mass of the SCZ. (The mass fraction of ^{14}N in the contaminating material has been taken to be the same as that in solar material.) Taking $\delta^{15}_{scz}(0) = -190$‰, the lowest composition yet reported in a lunar

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sample (5); $\delta^{15}_{\odot}$=+170‰, the value reported by (10) for the unique carbonaceous chondrite Renazzo; $\delta^{15}_{SCZ}(t)$=+120‰ and $t \cong 4 \times 10^9$yr (6); and $F_{SW}=1.04 \times 10^{12}$g/s gives $\Delta M_{SCZ} \approx 6.65 \times 10^{28}$g $=3.34 \times 10^{-5} M_{\odot}$. While this value for the SCZ mass is much smaller than the standard estimate of about $10^{-2} M_{\odot}$, Iben (11) has found very small values of ΔM_{SCZ} to be consistent with the observations of (12) concerning possible whole-body oscillations of the solar surface. With this estimate of the SCZ mass available a simple calculation for the mass accreted can be performed. For infalling compositions of δ^{15}_{acc}=-1000‰ (pure ^{14}N in the accretia) and δ^{15}_{acc}=-500‰ the resulting ΔM_{acc} is 2.05×10^{28} and 3.57×10^{28}g, respectively. We will then use 3.0×10^{28}g as a reasonable estimate of the total mass of accreted ^{14}N-rich material necessary to abruptly alter the SCZ from δ^{15}_{SCZ}=+170 to -190‰.

The model of (8) provides a convenient framework within which to examine the cloud parameters needed to insure the above accretion. Their equation [12] gives, for two extreme encounter velocities of 3 and 20 km/s and $\Delta M_{acc}=3.0 \times 10^{28}$g (taking the time over which accretion occurs to be 10^6yr), cloud number densities of n_{∞}=139 and $4.11 \times 10^4 cm^{-3}$, respectively. Both results are more than sufficient to overwhelm the present SW outflow insuring that accretion will indeed occur (9).

The concomitant effects of such an encounter on the earth's atmosphere can be gauged by relying upon the work of (9). Their formula [2] gives $\Delta M_{\oplus} \gtrsim 8.16 \times 10^{19}$g for a solar accretion of $\Delta M_{acc}=3.0 \times 10^{28}$g. This amounts to about 1.6% of the present terrestrial atmospheric mass. Had the primordial earth possessed N of composition akin to the value we have assumed for the early sun (i.e., $\delta^{15}_{\oplus}$=+170‰), this small accretion would be insufficient to produce the presently observed value of $\delta^{15}_{\oplus}$=0‰. Therefore, the composition of the earth's atmosphere is unlikely to owe its present character to the sort of cloud passage envisioned here. Considering that (9) have not taken into account the limiting influence of the earth's magnetic field in their model, this conclusion appears especially safe. In any event, the distinctly non-solar composition of terrestrial neon (which cannot be explained by the cloud passage proposed here as no corresponding secular variations in Ne have been observed among lunar samples in association with the N change) necessitates an additional gas reservior in the solar system. There is no reason why this same source cannot be the origin for terrestrial N as well as Ne. (See (10) for a discussion of the N variations found among meteorite classes, and (13) for the relative merits of different theories of atmospheric origins.) It is difficult to assess the importance of a cloud passage for the atmosphere-free moon. But for typical encounter velocities of 20km/s or less, the energy of implantation would be considerably smaller than 1 keV and quantitative retention of N under these condition is doubtful.

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Cloud typology. Hitherto we have not invoked any distinguishing properties for the encountered cloud apart from the necessary enhancement of ^{14}N relative to ^{15}N. This single distinctive characteristic, very low δ^{15}, is perhaps adequate to suggest a likely source for the cloud. Certainly, material processed through the CNO-cycle would possess this hallmark since seed CNO elements are thereby converted largely to ^{14}N. The necessity for our model of having this material in the ISM rather than a stellar interior, though, pinpoints planetary nebulae as candidate source objects worthy of closer scrutiny. Large enrichments of N and He in planetary nebulae have been demonstrated by observations of these objects in our galaxy and the Magellanic Clouds (14). Thus, the following scenario is offered: A planetary progenitor of a few solar masses formed in a cluster with the sun, probably with closely matching composition, evolved for a few times 10^8yr during which time its surface abundances of ^{14}N and ^4He were enriched, then ejected its outer envelope forming a nebula through which the early solar system passed. In this way, the miniscule probability of a random passage through such a nebula is obviated.

In the scenario presented here it is clear that any N isotopic effect introduced into the solar surface should be attended by a similar modification of the He isotopic composition. Material accreted from a ^{14}N-rich planetary likely had very low $^3He/^4He$ and thus a secular increase in this ratio for gases implanted in lunar soils would be anticipated. While evidence exists to support such a claim (15), it is not incontrovertible as both the lunar record and the theoretical understanding of He in the sun are complicated by numerous interfering effects. Nevertheless, the long-term increase in the $^3He/^4He$ ratio expected for our model is compatible with current interpretation of lunar data.

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LUNAR RADIONUCLIDE RECORDS OF AVERAGE SOLAR COSMIC RAY FLUXES OVER THE LAST TEN MILLION YEARS. Robert C. Reedy, Mail Stop 514, Los Alamos Scientific Laboratory, Los Alamos NM 87545.

The history of energic cosmic ray particles is recorded in lunar samples and meteorites. The sun causes many of the variations observed in cosmic ray fluxes. This paper reviews one part of this record: the fluxes of solar cosmic ray particles averaged over several time periods as determined from the activities of various radionuclides measured in lunar samples.

Nuclear interactions of cosmic ray particles with lunar samples result in many phenomena which can be used for different studies. Gamma rays made by cosmic ray-induced reactions have been detected in lunar orbit and used to map the distribution of several elements over the moon's surface. Stable and radioactive isotopes are produced by nuclear reactions. Heavy nuclei in the cosmic rays create radiation damage which can be etched chemically to reveal tracks. The nature of these cosmogenic isotopes and tracks first were characterized in detail, and now are routinely used for studies of the history of lunar samples. In the studies of these cosmic-ray nuclear interactions, information has been obtained about the history of the cosmic rays.

There are two sources of energetic cosmic-ray particles: the "galactic" cosmic rays (GCR), which originate outside the solar system and are modulated in the inner solar system; and the solar cosmic rays (SCR), which are emitted from the sun by large flares. The natures of these two types of cosmic ray particles and their interactions with the moon are discussed in (1). Both types of cosmic rays consist almost entirely of protons and alpha particles with a proton/alpha-particle ratio of about 10. There are only a few GCR particles per cm^2 per second, but their mean and median energies are of the order of 10^9 electron volts (1 GeV). These GCR particles can go several meters into the lunar surface and usually induce nuclear reactions in which many secondaries, including neutrons, are produced. The average integral flux of SCR particles above 10 MeV, averaged over many solar flares, is about 100 particles/cm^2 s, but the flux decreases rapidly with increasing energy and there are relatively few SCR particles with energies above 100 MeV. Most SCR particles are stopped by ionization energy losses in the top few centimeters of the lunar surface.

The production profiles for cosmogenic nuclides are similarly quite different for these two types of cosmic rays (1). The detailed profile for a given nuclide depends on the target chemistry and on the excitation functions (cross sections as a function of energy) for the production reactions. In general, the depth-activity profiles for GCR-produced nuclei are relatively flat or increase with depth to about 50 g/cm^2 in the lunar surface and decrease exponentially at greater depths. Activities of SCR-produced nuclei are highest at the lunar surface and rapidly decrease with depth, becoming much lower than GCR values below about 10 g/cm^2. Nuclides produced by low-energy reactions, e.g., Fe-56(p,n)Co-56 and Al-27(p,pn)Al-26, have large SCR/GCR production ratios near the moon's surface.

The flux of SCR particles as a function of energy can be determined from measured lunar radioactivities at several depths or for several different radionuclides, from the chemical abundances of target elements, and from the excitation functions for the major nuclear reactions. Uncertainties in the unfolded SCR fluxes can result from a limited number of measured activities, from poor precisions in the measured data, and from poorly known excitation functions. Further complications can arise from the history of the lunar samples, especially in the cases of long-lived radionuclides. Lunar rocks can be broken from bigger rocks, moved up and down in the lunar surface, and rolled

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to expose different parts. Even a rock with a simple exposure history (unmoved on the surface after its first excavation from a great depth in the moon) undergoes modification by erosion - having its surface slowly removed (at rates of the order of a millimeter per million years) by micrometeoroid bombardments and ion sputtering. Some material can be lost from the surfaces of non-igneous rocks (breccias) by handling (2). The lunar soils undergo considerable movement (gardening) because of meteoroid bombardment and are generally less suitable for study of SCR-produced radionuclides. Meteorites are not used for such studies because their orbits around the sun are not known and because their outer surface layers are removed by ablation while passing through the Earth's atmosphere.

Several models have been developed to calculate the depth-activity profiles for various radionuclides by GCR and SCR bombardment. Calculated GCR production profiles are necessary for corrections near the lunar surface where the SCR production occurs. In removing the GCR near-surface contributions, the absolute GCR production rates are determined from relative profiles normalized by activities measured in a deep sample with little or no SCR production. The shapes of the GCR profiles usually used (1) agree with those of others (3,4). Most SCR production rates are calculated ignoring secondary particles and assuming semi-infinite plane geometry, and the results of the model generally used (1) agree with those of at least one independent model (3). A Monte Carlo calculation (4) showed that reactions by SCR secondary particles are negligible relative to those by primary SCR particles and by GCR particles. A set of calculations done (2) assuming a hemisphere with a radius of 7 cm agreed with semi-infinite plane results near the surface where most of the important SCR production occurs.

Measurements have been made of depth-activity profiles for various radionuclides in a number of lunar rocks. The first results showed that 2.6-y Na-22 and 7.3 x 10^5-y Al-26, both produced by analogous reactions, had similar profiles and thus the average fluxes of solar protons over the last million years and over the previous few years were comparable (5). These early measurements also gave depth-activity profiles for short-lived radionuclides like 78.5-d Co-56 which were in very good agreement with profiles calculated using solar-proton fluxes measured by detectors on various satellites (5,6).

Since the Maunder minimum became generally accepted and raised questions about the constancy of the sun, the old measurements for short-lived radionuclides have been re-examined (6). Satellite measurements and depth-activity profiles for Co-56, Na-22, and 2.7-y Fe-55 revealed that the average flux of solar protons for solar cycle 19 (1954-1964) was about five times that during solar cycle 20 (1965-1975) (6). Most of solar-cycle 20's protons were emitted by the August 1972 flares (6) and, if the August 1972 flares had not occurred, the variation in average solar-proton fluxes would have been much larger (see Table I). Thus there were large changes in average solar-proton fluxes over the last few decades. The SCR-produced radionuclide with the next longest half-life, 12.33-y H-3, was not as well measured in lunar samples. Because only about 30% of the H-3 activity was made prior to 1954, not much could be learned quantitatively about solar-proton fluxes for earlier solar cycles.

There are no radionuclides with half-lives between those of H-3 and 5730-y C-14 which could be used for detailed SCR studies. The C-14 measurements of (7) gave an average integral flux of solar protons above 10 MeV of 200 protons/cm^2 s, which is about three times the average flux for the last few million years (8). I consider the solar-proton flux deduced from C-14 quite uncertain because the O-16(p,3p)C-14 excitation function was based on

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only a few cross sections measured by one group about 20 years ago. Additional cross-section measurements for this reaction are needed. Solar protons also produce radiation damage in the tops of lunar rocks which can be studied by thermoluminescence (TL) measurements. The half-life for such damage and TL studies is about 2×10^3 years (9). The TL data for one lunar rock implied an integral flux of solar protons above 10 MeV of 40-80 protons/cm^2 s (9), considerably below the C-14-deduced flux.

Again there is a half-life gap for solar-proton-produced radionuclides until 7.3×10^5-y Al-26. Solar alpha particles can produce 8×10^4-y Ni-59 by the Fe-56(α,n)Ni-59 reaction. There are very few measured Ni-59 activities and there are considerable uncertainties in the reported activities. The average integral flux of solar alpha particles with energies above 10 MeV is of the order of 10 /cm^2 s (10).

Rocks which have been placed on the lunar surface within the last few million years have been used to complement results for various long-lived radionuclides. Surface exposure ages are well determined from measured concentrations of GCR-produced nuclides and from tracks produced by heavy nuclei. Measurements of Al-26 in four rocks with exposure ages ranging from 0.5 to 3.7 million years showed less than ± 25% variation in average solar-proton fluxes (11). Depth-activity measurements of Al-26 and 3.7×10^6-y Mn-53 in several lunar rocks showed that the average fluxes of solar protons over the last 2- and about 10-million years are very similar (8). Table I summarized all the average solar-proton fluxes discussed above.

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TABLE I. Average Solar-Proton Fluxes over Various Time Periods as Determined from Lunar Radioactivity Measurements.

Time Period (Ref.)	Integral Flux (protons/cm^2 s)		
	E > 10 MeV	E > 30 MeV	E > 60 MeV
1965 - 1975[a] (6)	89	28	8.0
1965 - 7/72[a] (6)	25	4.2	0.9
1954 - 1964[a] (6)	378	136	59
$\sim 5 \times 10^3$y (TL) (9)	40-80	9.5-19	4-8
$\approx 10^4$y (C-14) (7)	200	72	26
$\approx 10^6$y (Al-26) (8)	70	25	9
$\approx 5 \times 10^6$y (Mn-53) (8)	70	25	9

[a] Averaged over 11 years.

RADIONUCLIDES AS SOLAR COSMIC RAY MONITORS--AN IMPROVED MODEL. G. P. Russ III and M. T. Emerson*, Department of Chemistry and Hawaii Institute of Geophysics, University of Hawaii at Manoa, Honolulu, HI 96822

Measured depth profiles of solar cosmic ray (SCR) produced radionuclides in lunar rocks have been shown to be useful probes for determining the average flux and energy spectrum of SCR protons over a time scale of a few half-lives. Such studies have been made for nuclides with half-lives and therefore sampling intervals ranging from 10^{-1} to 10^{7} yr (1,2,3,4). In addition to providing a record of the ancient sun, a knowledge of the SCR flux allows one to interpret radionuclide profiles observed in lunar soils in terms of meteorite induced regolith mixing (5). In general the time interval investigated is constrained by the time of sample collection on one end and the radioactive decay of the measured nuclides on the other. In the case of rock 68815 (4) the total exposure interval was well defined by the ^{81}Kr-Kr method as the last 2 Myr (6). Depth profiles of ^{53}Mn ($t_{\frac{1}{2}}$ = 3.7 Myr) and ^{26}Al ($t_{\frac{1}{2}}$ = 0.72 Myr) measured with sampling intervals as thin as 0.5 mm on three faces of this rock provide a data base to [1] compare production rates of these nuclides in a discrete time interval, [2] determine the average SCR flux and energy spectrum over the last 2 Myr, [3] compare the 2 Myr flux to the average over ~10 Myr as measured by other lunar rocks and to the recent flux, and [4] look for anisotropy in the SCR flux.

In order to deduce the SCR record from radionuclide measurements, one must be able to model the radionuclide activity within a sample as a function of the number of incident particles, their energy or rigidity spectrum, chemical composition, exposure interval, position within the rock, and erosion rate of the sample's surface. The calculations most commonly used to interpret measured activities are those of Reedy and Arnold (7) who calculated activity as a function of depth below the surface of a plane and for a vertical, radial column in hemispherical rocks. Using this model it has been possible to approximately fit the measured ^{53}Mn and ^{26}Al vertical profiles in lunar rocks with a single but not unique set of SCR parameters--characteristic rigidity (R_o) = 100 MV and flux (J) = 70 $p \cdot cm^{-2} \cdot sec^{-1}$ (E>10 MeV, 4π)--by allowing the erosion rate to vary between 0.5 and 2.2 mm/Myr. However this agreement may be fortuitous and the absolute values of R_o and J may be incorrect because the sample size required for analysis precludes sampling along radial columns. The rocks are also not hemispheres. For the sloping faces of 68815 the basic Reedy-Arnold calculation is clearly inadequate to properly interpret the data (4). Bhattacharya et al. (8) have expanded the calculations to include activities at arbitrary points within ellipsoids, but this work does not treat surface roughness which is large compared to the sampling depths or sampling which averages over appreciable volume.

In the process of sampling rock 68815, surface contour maps (1.4 mm grid spacing and ±0.05 mm vertical precision for the outer samples) were measured before sampling and between each layer. These data allow calculations of activity on a point-by-point basis within the rock taking into account its actual shape and lunar orientation. The point-by-point activities can then be averaged to obtain predicted activities for various R_o's, J's and erosion rates which are directly comparable to the data. The results of these calculations will be presented. While the specific motivation for this work was the interpretation of the 68815 data, the technique is applicable to any sample for which the surface and sampling geometry can be described. (1) Finkel R. C. et al. (1971) Proc. Lunar Sci. Conf. 2nd, p. 1773-1789. (2) Wahlen M. et al. (1971) Proc. Lunar Sci. Conf. 3rd, p. 1719-1732. (3) Imamura M. et al. (1974) Proc. Lunar Sci. Conf. 5th, p. 2093-2103. (4) Kohl C. P. et al. (1978) Proc. Lunar Sci. Conf. 9th, p. 2299-2310. (5) Nishiizumi K. et al. (1979) Earth Planet. Sci. Letters, in press. (6) Behrmann C. (1973) Proc. Lunar Sci. Conf. 4th, p. 1957-1974. (7) Reedy R. C. and Arnold J. R. (1972) J. Geophys. Res. 77, p. 537-555. (8) Bhattacharya S. K. et al. (1973) The Moon 8, p. 253-286.

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STATISTICAL NATURE OF THE SOLAR ACTIVITY IN THE PAST AS RELATED TO SOLAR COSMIC RAY PRODUCTION,

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At present, the secular variation of the solar activity is investigated by analysing various nuclides induced by solar cosmic rays in lunar and meteoritic samples (e.g., Fleischer et al., 1975). Since the half life for the decay of these induced nuclides is different from each other, we may select some specific nuclides to study the variation of the solar cosmic ray density at the earth for different time intervals as 10^2, 10^3, 10^6 or 10^8 years. By using the data recorded in lunar rocks and meteorites, at present, it is, therefore, possible to investigate the general trend of the solar activity variation for 10^8 years or more.

It is known, furthermore, that, for the solar activity in the past, there existed some unusual periods such as the Maunder Minimum and the Grand Maximum (e.g., Eddy, 1976). It is also clear that the solar activity for the cycles Nos. 18, 19 and 20 was unusually high among those for the last 200 years since the above minimum (Sakurai, 1979). As discussed above, except for the eleven-year variation, the mean trend of the solar activity change cannot be considered as constant for the time longer than 100 years.

The observational data on the relative sunspot numbers are available for the last 360 years since the discovery of sunspots by Galileo, Scheiner, Harriot and others around 1610. In this paper, the sunspot data for 182 years from 1784 to 1975 are statistically analysed in order to find the nature of the solar activity and its long-term variation. At first, the statistical distribution of the annual mean sunspot numbers has been obtained for these years as shown in Fig. 1. The two highest numbers, 190.2 and 184.8, were observed in 1957 and 1958, respectively. In this figure, three lines to give the expectation for the above distributions for 10^3, 10^4 and 10^5 years are drawn by extrapolating linearly the result obtained for the data for 182 years. By referring to these lines, the general trend of the solar activity variation can be estimated for such longer periods.

It is known that the occurrence frequencies of solar flares of different importances are roughly proportional to these sunspot numbers (Kiepenheuer, 1953). Therefore, the relation of these frequencies to the solar activity has been examined for the data for the cycle No. 19 and obtained as shown in Fig. 2. This result indicates that the occurrence frequency decreases exponentially with the flare importance. Hence the occurrence of flares of importances greater than 5 is never expected for the solar cycles that the highest annual sunspot numbers are about 200. However, it is expected from Figs. 1 and 2 that, for the cycle of the maximum sunspot numbers to be 400, solar flares of importances 5 and 6 may occur about 15 and 2 times, respectiveley (Sakurai, 1979). Since such cycles just mentioned are to be observed 100 times for the period of 10^4 years (Fig. 1), the periods for the solar activity much higher than that currently observed must have occurred during the recent past history. Therefore, the production rate of solar cosmic rays must have also been higher for these periods. Thus it seems that, for such

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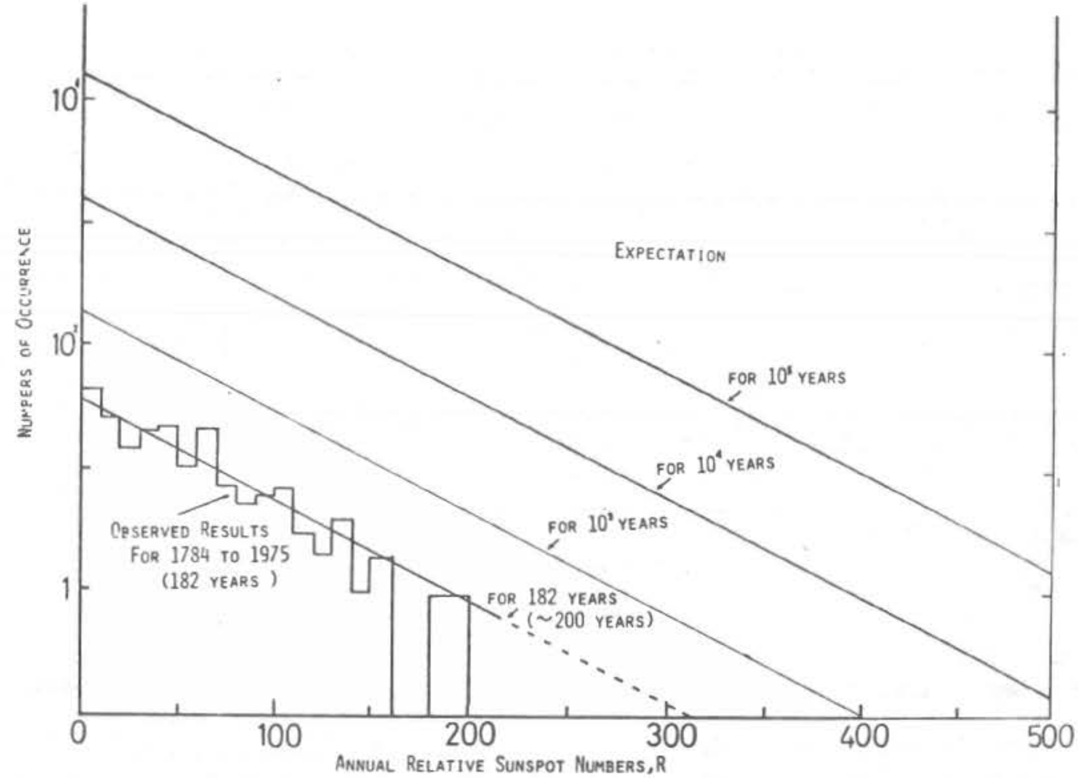

Fig. 1 Distribution of the annual relative sunspot numbers for the years from 1784 to 1975. The lines drawn indicate the occurrence frequencies for these numbers as expected for 10^3, 10^4 and 10^5 years.

periods, the background density of solar cosmic rays at the earth's orbit was much higher than that expected from the present solar activity.

It has been shown that, during the most of the medieval age from 900 to 1300 A.D., the solar activity was higher compared with that observed during the recent cycles Nos. 18, 19 and 20, though these cycles were also very active in the solar activity for the last 200 years (see Fig. 1). Hence, this age is now called the "Medieval Maximum" or "Grand Maximum." According to Fireman (1973), the production rate of solar cosmic rays for the last 1000 years must have been higher than that currently observed. Thus it may be said that the active periods as the Grand Maximum or more active periods must have occurred for 10^4 years, for instance. The existence of such periods may be seen in the lunar samples as analysed by Zook et al. (1977).

Although the sunspot data for about 200 years were only statistically analysed to estimate the solar activity in the past, they have shown to be useful for the comparative study of the solar activity and its relation to solar cosmic ray production in the recent past. If the period that the solar activity was higher as that observed during the Grand Maximum would be prevailing for a few hundred years, the background density of solar cosmic rays at the earth's orbit must be higher than that currently observed and then the earth's environmental condition

THE SOLAR ACTIVITY IN THE PAST

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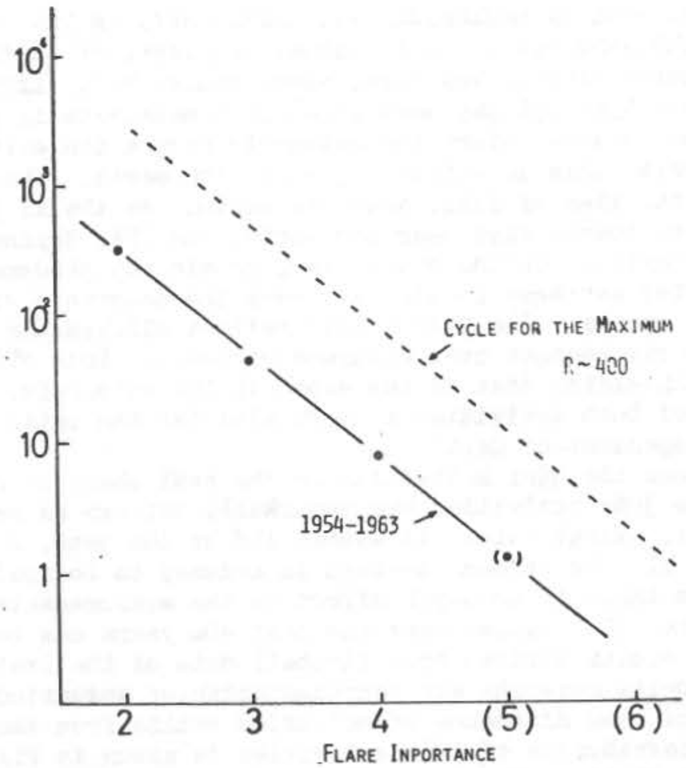

Fig. 2 reproduced courtesy of *Astrophys. Space Sci.*

Fig. 2 The numbers of solar flare occurrence for the cycle No. 19 as shown with respect to the flare importance. These numbers expected for the cycle with the maximum sunspot numbers of 400 are also shown by dotted line.

must have also been strongly influenced by the bombardment of these particles on the earth.

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^{37}AR AND ^{39}AR IN METEORITES AND COSMIC RAYS IN THE SOLAR SYSTEM DURING THE LAST THOUSAND YEARS. O.A. Schaeffer, Dept. of Earth and Space Sciences, State University of New York, Stony Brook, N.Y., 11794.

The cosmic ray 37Ar (50 day mean life) in a meteorite is produced largely during the 50 days before the meteoroid struck the earth. For most meteoroid orbits this is within 0.5 AU of the earth. The 37Ar is produced then at the time of fall, near the earth. As the 11 year solar cycle modulates the cosmic rays near the earth, the 37Ar depends mainly on the 11 year solar cycle. On the other hand, cosmic ray produced 39Ar (390 year mean life) averages cosmic rays over the meteoroid orbits encomposing many solar cycles. The 39Ar should reflect differences in meteoriod orbits and cosmic ray changes over hundreds of years. Both 37Ar and 39Ar are dependent on shielding that in the depth in the meteoroid. As the depth dependence of both activities is very similiar the ratio of the activities is independent of depth.

If one examines the 39Ar activities in the FeNi phase of chondrites one finds that the 39Ar activities are remarkably uniform as measured in over 30 falls. All except a few lie within 10% of the mean, 22.3 dpm/kg (see ref. 1). If all the spread observed is assumed to be real and if it is assumed that there is no depth effect in the measurements, a maximum gradient in the solar system over the past 400 years can be estimated.(1) Assuming that the orbits derived from fireball data of the Prairie (2) and European (3) meteorite networks are representative of meteoriod orbits then the distribution of mean distances of meteoriod orbits from the sun is given in Fig. 1. The distribution of 39Ar activities is given in Fig.2 as well as calculated distributions based on different cosmic ray gradients from 7.5% to 12.5%/AU. Evidently the average gradient is less than 10%/AU. As some of the spread in 39Ar activities is due to experimental error and depth of shielding, therefore it seems reasonable that the average cosmic ray gradient for particles above 200Mev in energy was less than 10%/AU during the last 400 years and probably not much different than that measured presently by Pioneer 10 and 11 and Helios at a time near solar minimum. (4)

In Fig. 3, the 37Ar activities are plotted versus the Mt. Washington neutron monitor rate (two months average preceeding the date of fall). The neutron monitor rates were partly taken from Begemann (5) who made similiar considerations. The neutron monitor rate is in excellent anticorrelation with sunspot number which reflects the galactic cosmic ray flux at 1AU. The 37Ar should therefore be proportional to the neutron monitor rate. The diagram shows a wide scatter around the best fit straight line. The activities range from 5 to 29 dpm/kg. The difference cannot be explained by orbits, solar activity or shielding effects. Shielding effects should vary the 39Ar as well but the plot of 39Ar activity versus recovered mass shows no dependence on mass for the samples studied. It seems as if the dispersion in the 37Ar is due to some artifact of the measurements. If the very low values are omitted, the remaining 37Ar activities follow the neutron monitor counting rate reasonably well. On the basis of cross-section measurements, the cosmic ray production rate of 37Ar is about 90% that of 39Ar.(6) Yet it has been pointed out by Forman et al (7) that the Ar39 activities are about 20% higher than most of the 37Ar activities and not as to be expected equal to the mean. On this basis, the average recent level of 39Ar activity should be 19 ± 2 dpm/kg while the observed value is 22.3 ± 1.6 dpm/kg. This means that

37AR AND 39AR IN METEORITES

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the average level of interplanetary cosmic ray flux on these meteorites, averaged over long times (hundreds of years) was larger than the recent flux levels at the earth during most of the last two solar cycles and only two percent less than at recent solar minimum. This supports the idea suggested by Eddy (8) that there was a prolonged minimum in solar activity before 1715, during the Maunder minimum in sunspot activity, which caused the DeVries maximum in 14C in the earth's atmosphere by reducing the amount of cosmic ray modulation in interplanetary space.

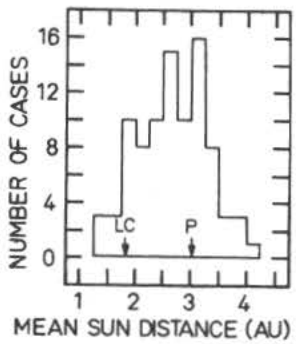

Fig. 1. Distribution of meteoroid orbits intersecting the earth's orbit. L.C. Lost City, P. Pibram.

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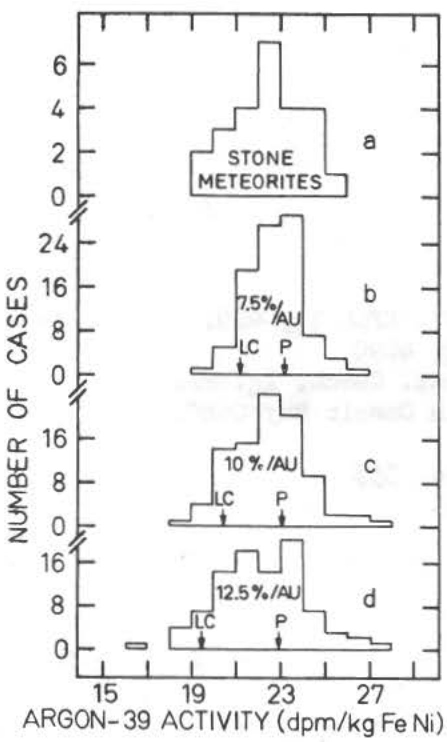

Fig. 2. Distribution of 39Ar activities in meteorites for different spatial gradients of galactic cosmic rays.

^{37}AR AND ^{39}AR IN METEORITES

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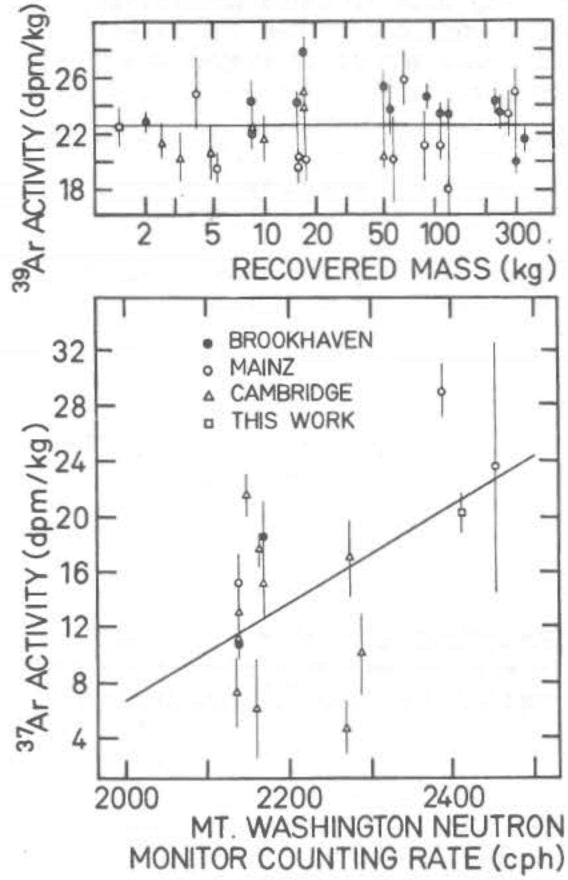

Fig. 3. ^{37}Ar and ^{39}Ar activities in meteorites as a function of recovered mass and neutron monitor rate.

Fig. 3 reproduced courtesy of *Earth Planet. Sci. Lett.*

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SUNSPOT STRUCTURE AND THE CLIMATE OF THE LAST ONE HUNDRED YEARS.

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Whether or not the sun's luminosity varies over time scales of decades is not known to an accuracy better than ~1%. Since a change in solar irradiance of order 1% could have a significant effect on climate, it is of interest to consider any feature of solar activity which might be an indicator of total luminosity. The average number of sunspots has often been proposed to be such a feature, though Robock (1) has found that simple climate models based on constant solar irradiance modulated by volcanic dust provide a much better fit to the observed temperature record than models based on solar variability as given by sunspot number. However, physically it seems plausible that changes in the sun's convection zone can lead to changes in luminosity, and there is some evidence that sunspot structure is sensitive to the strength of convection. Hoyt (2) has therefore suggested that the average umbral/penumbral area ratio ("U/P") is an index of solar luminosity.

To model the implications of this hypothesis for climate, the following time-dependent global energy balance equation was integrated to yield a calculated temperature record that could be compared with the observed record,

$$C\frac{dT_s(t)}{dt} = \frac{E_s(t)}{4}(1-\alpha) - E_L(t) \quad , \tag{1}$$

where T_s is the mean global surface temperature, E_s is the mean solar irradiance reaching the lower atmosphere, E_L is the long wave irradiance of the earth, α is the mean planetary albedo, C is the heat capacity at constant pressure for a unit cross-section of the atmosphere and an assumed global ocean mixed layer, and t is time. Following Budyko's (3) parameterization of E_L, we write

$$E_L(t) = A + BT_s(t) \quad , \tag{2}$$

where A and B are empirical constants. If E_s = constant, $T_s = T_e$, the planetary radiative equilibrium temperature, where

$$T_e = \frac{1}{B}\left[\frac{E_s}{4}(1-\alpha) - A\right] \quad , \tag{3}$$

and any small temperature perturbation will decay exponentially with a time constant of C/B.

Two ways in which E_s can vary are through: (1) intrinsic variations in the total solar output; (2) variations in the optical transmission properties of the atmosphere, which we assume are due solely to volcanic dust. For the first case we assume

$$E_s'(t) = G + H\frac{U}{P}(t) \quad , \tag{4}$$

where E_s' is the mean solar irradiance at the top of the atmosphere. The constants G and H can be determined from two conditions on E_s', which we have chosen as

$$E_s'(1969) = 1369 \text{ Wm}^{-2} \tag{5}$$

and

$$\frac{E_s'(1935) - E_s'(1969)}{E_s'(1969)} \equiv \varepsilon \geq 0 \quad , \tag{6}$$

where (5) is taken from Willson (4) and ε is a parameter of the model. For the second case we assume that colcanic dust from major eruptions results in an equivalent decrease in solar irradiance, such that

$$E_s(t) = E_s'(t) \left(1 - \Theta \frac{V(t)}{V(1963)}\right) , \tag{7}$$

where V is either Lamb's dust veil index (5) or Mitchell's stratospheric dust loading (6), both for the northern hemisphere, and θ is the magnitude of the effective decrease in solar irradiance assumed due to the Mount Agung eruption of 1963.

By picking "reasonable" values of C, A, B, and α, and specifying ε and θ, equation (1) can be integrated over the time period that a record for U/P is available, namely 1874-1970, to give a calculated temperature record, which can be compared to the northern hemisphere record compiled by Budyko (3) and extended by Angell and Korshover (7). A linear warming due to exponentially increasing atmospheric carbon dioxide was crudely estimated by using a linear least squares fit between the observed and calculated records. Some of the model results are shown in Table 1 and Fig. 1.

Table 1

Model	ε	Θ	Volcano Chronology	$\Delta T(CO_2)$	C
1	0	.001	Lamb	.34	.745
2	0	.004	Lamb	.10	.766
3	0	.007	Lamb	-.14	.767
4	0	.001	Mitchell	.36	.751
5	0	.004	Mitchell	.16	.763
6	0	.007	Mitchell	0	.766
7	.002	0	-	.30	.726
8	.004	0	-	.18	.724
9	.006	0	-	0	.724
10	.002	.003	Lamb	0	.803
11	.002	.003	Mitchell	0	.789

All models: $A = 209\ Wm^{-2}$, $B = 1.83\ Wm^{-2}\ (°C)^{-1}$, $\alpha = .285$, $C = 3.14 \times 10^8\ j\ m^{-2}\ (°C)^{-1}$ (value of C assumes 75 m depth of global ocean mixed layer).

$\Delta T(CO_2)$: Total CO_2 warming, in °C, from 1880-1970.

C: Correlation coefficient between observed northern hemisphere temperature record and calculated record (including CO_2 warming).

Several points seem clear: (1) according to the correlation coefficient between the observed and computed records, both the solar variability models ($\varepsilon \neq 0$, $\Theta = 0$) and the volcanic dust models ($\varepsilon = 0$, $\Theta \neq 0$) can give equally good fits to the observed record, unlike Robock's results mentioned earlier; (2) the variable sun models can fit the cooling part of the record better, when volcanic activity was low, whereas the volcanic dust models can fit the warming part of the record better, and the mixed models ($\varepsilon \neq 0$, $\Theta \neq 0$) marginally give the best

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overall fit; (3) neither ε or θ can be very large if a warming by carbon dioxide is real; (4) it does not appear necessary to invoke random fluctuations in the climate system to explain secular trends in surface temperature, although such internal forcing may well account for the greater noisiness in the observed record.

These results are based on simple highly parameterized models using data of varying reliability and therefore cannot be taken too literally. Nonetheless, they are sufficiently suggestive that we urge efforts be made to: (1) determine, to an accuracy ≤0.1%, any variability in solar luminosity over a period of at least a few decades; (2) understand any possible physical links between solar variability and climate; (3) understand better the physics behind available historical and proxy records of solar activity, like the U/P data, in order to better utilize such records.

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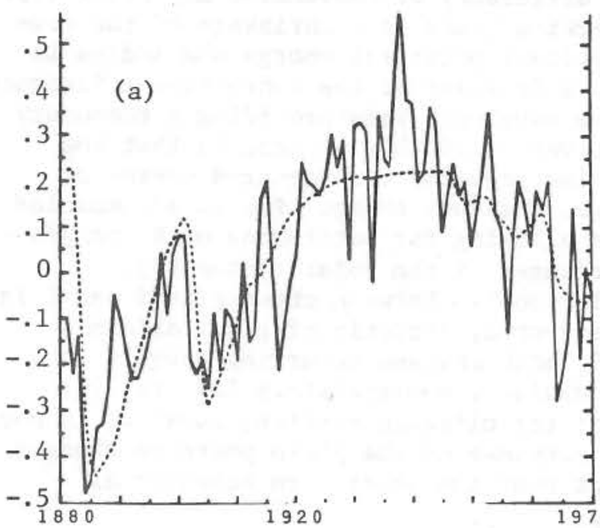

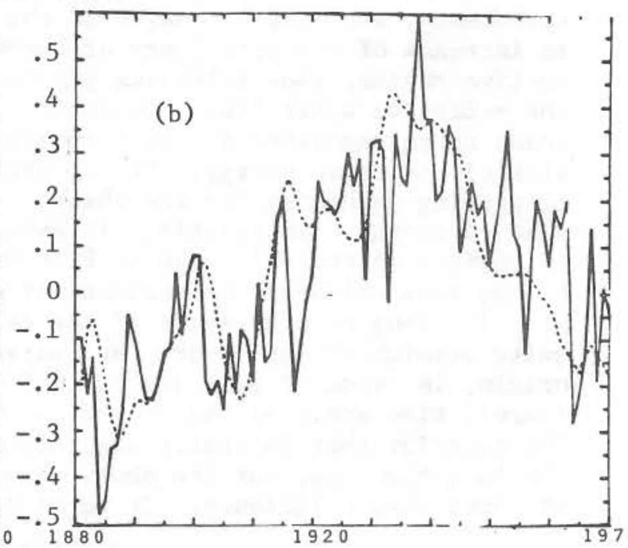

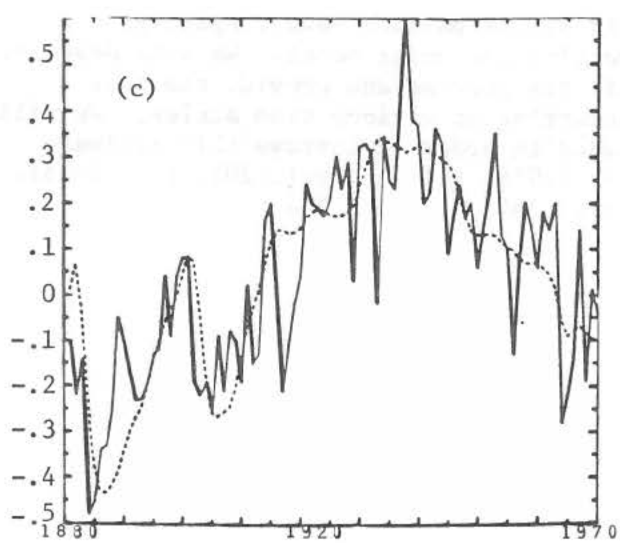

Fig. 1 Temperature anomalies (in °C) versus year (1880-1970). Solid line is observed northern hemisphere record and dashed lines are calculated records. a) Mitchell chronology, ε = 0, Θ = .005, $\Delta T(CO_2) = 0$; b) ε = .004, θ = 0., $\Delta T(CO_2) = .0$; c) Mitchell chronology, ε = .002, Θ = .003, $\Delta T(CO_2) = 0$.

NATURE OF THE CLIMATICALLY SIGNIFICANT CHANGES OF THE SOLAR CONSTANT.
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Possible changes of the solar constant, S, which are of significance to climate studies involve changes at the few parts per thousand level in time scales of the order of years to hundreds of years. The extreme stability of the radiative solar interior, coupled with its long thermal time scale (about 10^7 yrs.), precludes this region from producing climatically significant changes of S. Moreover, since the nuclear energy generating region is wholly contained in the innermost portion of the radiative core, changes in nuclear energy output cannot play a role. Consequently, if climatically significant changes of S do occur, they must be produced by processes in the solar convective envelope, involving non-nuclear energy sources or sinks.

Within the above scenario, two processes are of possible significance. The first is solar activity. However, the small size of the frequency-integrated flux contribution due to active regions, and the lack of a convincing correlation between solar activity and the value of S dispute the effectiveness of this mechanism. The second mechanism arises from the turbulent nature of the convective envelope. Because of the unstable nature of turbulence, stochastic changes in the efficiency of convection may occur (1). An increase of the efficiency of convection leads to a shrinkage of the convective region, thus releasing gravitational potential energy and adding to the radiative solar flux. Conversely, a decrease of the convective efficiency leads to an expansion of the convective envelope, thus providing a temporary sink of radiative energy. The attractiveness of this process is that the triggering mechanism for the changes also provides the required source or sink of energy. In addition, it assures that any change of S is accompanied by changes in the solar radius R, thus allowing for monitoring of S changes by the less difficult measurement of changes of the solar radius (2).

The long term behavior of the relationship between changes in S and R is quite straightforward since the increase of S, strictly of gravitational origin, is produced by a decrease of R, both changes occurring roughly on a thermal time scale of the convective envelope, approximately 10^5 yrs. (2). The behavior that is really significant for climatic studies, however, is not the long-term one, but the short-term response of the photosphere to changes in convective efficiency. It turns out that the short-term behavior of

$$W = (\Delta R/R)/(\Delta S/S)$$

is critically dependent on the details of the physics (e.g., opacity, equation-of-state, etc.) used in computing the solar model. We will describe the results of extensive modelling of this process and provide the best current estimate of W, for changes occurring on various time scales. We will also discuss what further work is needed in order to improve this estimate.

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RECORD OF EARLY MAGNETIC FIELDS IN THE SOLAR SYSTEM. D.W. Strangway and N. Sugiura, Dept of Geology, Univ. of Toronto, Toronto, Ont. M5S 1A1.

The record of magnetic fields present in the early history of the solar system has been difficult to recover because of extensive reworking and reheating of surface rocks on the earth (Table I). This causes them to be remagnetized and obliterates the earlier record. Clear evidence of ancient fields from rocks as old as 2.8 billion years have been reported by a number of authors (Irving and Naldrett, 1977). We infer from this that the earth had a dynamo and hence a fluid, metallic core at this time and presumbably for most of the history of the earth. This means that the earth carries no memory of other fields in the solar system. Nevertheless, the methods used to measure the record of the ancient terrestrial field can be applied to the study of meteorites and of lunar samples.

Meteorites are samples that are dated at 4.6 b.y. and are generally considered to be samples of the early solar system. In addition they contain chondrules which were formed in an event or series of events that predate the assembly of the meteorite, although they do not show significantly earlier dates. It has been possible to determine the strength of two ancient fields. The Allende meteorite for example appears to have assembled in the presence of a field of about 1 oersted at a temperature of 200–300°C (Banerjee and Hargraves, 1972), while individual chondrules appear to have cooled from high temperatures in fields of varying strength but as high as 10 oerstes (Lanoix et al, 1978). Further, the chondrules appear to have their magnetizations in random orientation suggesting that they have not bee remagnetized since they were assembled into the meteorite.

Nagata (1979) has recently reported on paleointensities determined from some achondrites and indicates that they formed in a field of about .1 oe. The meteorite record thus suggests that the interplanetary field varied from 10 oe (chondrules) to 1 oe (chondrites to 0.1 oe(achondrites) which is the time sequence of formation. It clearly infers the presence of large fields in the earliest phases of the solar system.

The study of lunar samples and magnetic mapping of the moon suggests that impact breccias which formed 4.0 b.y. ago formed in the presence of a local field of 0.01-0.1 oersteds as did basaltic rocks which range in age from 3.2-3.9 b.y. Strangway (1977). It is probable that these samples were magnetized in an internal field. There is controversy over whether this field was due to an early dynamo which has subsequently stopped or whether it was due to a moon magnetized during accretion and which has subsequently warmed above the Curie point (Runcorn, 1975; Strangway and Sharpe, 1975). If it is due to the accretion phase, we have an indirect record of early solar system fields preserved in the lunar magnetic field patterns. It has been pointed out that there is a preferred orientation to these anomalies which tend to group around an east — west direction in the equatorial plane (Strangway et al., 1973; Hood et al., 1978). The geometry which could cause such a distribution of directions is not clear.

In the same manner, it is possible to examine the magnetic dipole moments of the planets to see if they carry any information about early solar system fields. Mercury has a significant dipole moment which might be related to a current dynamo (Acuna and Ness, 1976). Alternatively it may have become magnetized in early solar system fields when its crust cooled in the presence of such a field (Sharpe and Strangway, 1976). There is a definite possibility that the outer part of Mercury carries a record of the fields present when the planet formed. The surface temperature of Venus is sufficiently high that it cannot be expected to carry much of a record. It has at most a very small dipole moment and hence does not have a modern dynamo either (Russell et al, 1979). Mars is reported to have a dipole moment. Since part of this planet preserves early features -- highly impacted -- it is possible that Mars contains a record of the magnetic field present when the crust cooled.

The evidence for early solar system fields is sketchy, but it suggests that large fields existed. We do not know the cause of these fields. In Figures 1 and 2 we illustrate two possible causes. In the one case a large solar dipole field would have magnetized the meteorites and the planets. Because of the relation to the rotation axes this seems quite possible. It does not however, explain the equatorial meoments on the moon unless its axis changed by 90° after magnetization (Fig. 3). Alternatively, a large solar wind field could have done the magnetizing, but it is then difficult to explain why the field is along the rotation axis.

To test these various hypotheses much more needs to be done, especially in the study of meteorites and their contained chondrules. Studies of the magnetic fields associated with small objects such as asteroids would also be of interest.

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Record of Early Magnetic Fi^lds in the Solar System.

D.W. Strangway

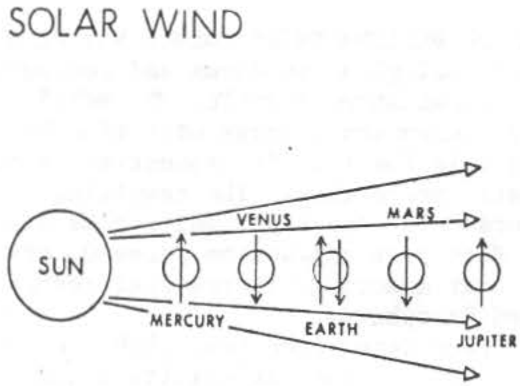

Fig. 1 Solar wind model for magnetizing planets would not give axial components.

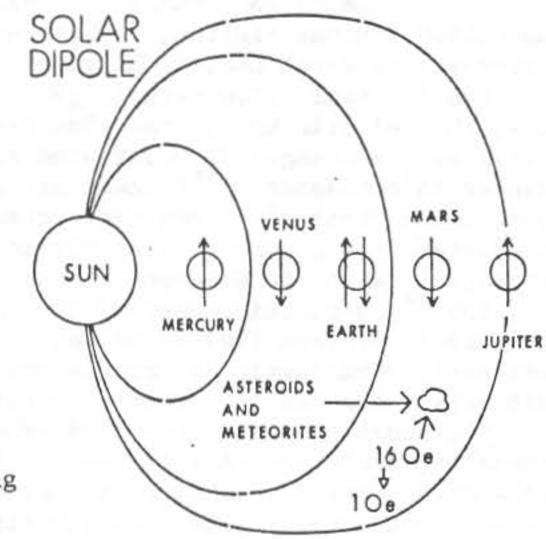

Fig. 2 Solar Dipole would give give planets an axial component during accretion or cooling.

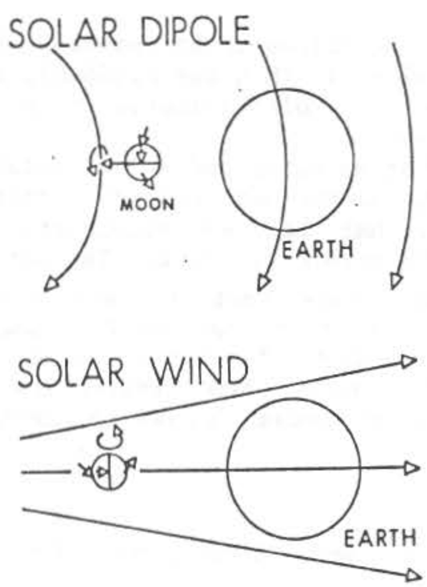

Fig. 3 The Moon has radial components in its magnetic field consistent with a solar wind field or a solar dipole if the rotation axis tilts.

	DIPOLE mmt	SURFACE FIELD
MERCURY	5.1×10^{22}	370 nt
VENUS	$1-2.5\times10^{21}$	< 6-16
	6.5×10^{22}	30
EARTH	8×10^{25}	31,000
MOON PRESENT	$<1.3\times10^{18}$	<0.02
MOON PAST	$\sim10^{23}$	2,000
MARS	2.4×10^{22}	64
JUPITER	1.44×10^{30}	402,000
CHONDRITES	—	100,000
CHONDRULES	— upto	1,600,000

Table I. Dipole Moments and Surface Fields of the planets.

TREES AND THE ANCIENT RECORD OF HELIOMAGNETIC COSMIC RAY FLUX MODULATION. Minze Stuiver, Departments of Geological Sciences and Zoology, Quaternary Research Center, University of Washington, Seattle, WA 98195

The ^{14}C production rate in the upper atmosphere changes with time because the galactic cosmic ray flux responsible for the ^{14}C production is modulated by the changes in solar wind magnetic properties. The resulting changes in atmospheric ^{14}C level are recorded in tree-rings and can be used to calculate past ^{14}C production rates. Such past production rates Q_M are calculated from a carbon reservoir model that describes terrestrial carbon exchange between the atmosphere, ocean and biosphere.

The ^{14}C production rates Q have also been determined from 20th century atmospheric neutron fluxes and can be related to solar variability as expressed by geomagnetic Aa indices and sunspot numbers S. An inverse relationship exists between ^{14}C production rate Q and S, as well as Q and Aa.

The sunspot record, obtained from historical observations over the past centuries, indicates an interval in the late 17th century during which sunspots were nearly absent (the so-called Maunder Minimum). The empirically derived 20th century Q/Aa relationship, when extrapolated to Aa=0, predicts an increase in ^{14}C production rate of 23 ± 6 percent above average. Evidently the solar wind interaction with the earth's magnetosphere, as expressed in Aa indices, was nearly absent during the Maunder Minimum because the carbon reservoir calculated Q_M values are 21 percent above average for the same interval. Time patterns of the observed sunspot record and calculated Q_M record also are in agreement.

The ^{14}C record for the current millennium indicates three episodes where sunspots apparently were absent, viz. at AD 1654-1714 (Maunder Minimum), at AD 1416-1534 (Spörer Minimum) and at AD 1282-1342 (Wolf Minimum). A less precisely defined minimum occurred near AD 1040.

The above relationships between ^{14}C production rates and solar variability (i.e., Aa, S) make it possible to calculate approximate sunspot numbers and Aa indices from the ^{14}C record by assuming that these variations are caused predominantly by solar modulation of the cosmic ray flux. The agreement between predicted Q and calculated Q_M values shows that this assumption, at least for the last 300 years, is reasonable. However, one has to examine the possibility that some of the changes in atmospheric ^{14}C may be caused by climate induced internal re-distribution of ^{14}C between carbon reservoirs, or possibly by ^{14}C production rate changes related to global changes in earth geomagnetic field intensity.

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EVIDENCE OF SOLAR VARIABILITY ON THE PLANETS Owen B. Toon, James B. Pollack, Kathy Rages, Space Science Div. NASA-Ames Research Center, Moffett Field, CA 94035

The Earth is a dynamic planet and the effects of solar variability are masked by other changes such as those due to continental drift or the evolution of the atmosphere. Synchronous changes on the Earth and the planets would be strong evidence for solar variability since the sun is one of the few common parameters between the planets. The search for such synchronous changes is in its infancy, but two strong coincidences have been found: one between the Earth and the outer planets at very short periods (decades); and one between Mars and the Earth at very long periods (10^9 years).

It is well known that the Earth's surface temperature has been maintained just slightly above the freezing point of water for billions of years despite the fact that astronomical theories suggest the sun's luminosity was much lower a billion years ago. The presence of extensive ancient river beds on Mars suggests that billions of years ago Mars was very much warmer than at present. Hence both Mars and Earth present negative evidence for the theoretical increase in solar luminosity during the sun's evolution. The popular resolution of this dilemma is that the atmospheres of both Mars and Earth have evolved in just such a manner as to offset the early low solar luminosity by having early atmospheres capable of trapping infrared radiation efficiently and warming the surface through a greenhouse effect. It was first suggested that these early atmospheres were rich in reduced compounds especially NH_3. However, more recently early atmospheres enriched in CO_2 have been advanced because they are photochemically more stable, and they are more obviously related to the volatile inventories of the terrestrial planets. It is imagined that early in their histories Venus, Mars, and Earth each outgassed massive CO_2 atmospheres. Since it was closest to the sun, Venus never lost its CO_2 atmosphere and it slowly warmed up as the solar luminosity increased. The CO_2 atmosphere on Earth was lost by geochemical processes, but continental drift recycles some CO_2 to the atmosphere helping to maintain our present climate and the Earth's present orbital configuration allows sufficient water vapor into the atmosphere to maintain the climate. Mars lost its CO_2 by geochemical processes that had no recycling mechanism. Due to its greater distance from the sun, Mars lost its greenhouse. If the terrestrial planets did follow this scenario and did not have extensive reduced atmospheres, then the best place to search for evidence of a lower initial solar luminosity is Venus. Early in its history Venus may have had an Earth-like climate, and the scars of this climate may remain on its surface to be discovered by radar mapping of the surface in the next several years.

When they were first discovered the river beds on Mars were thought to be rather young because of their uneroded appearance. At that time parallels were drawn between a possible 10^7 year ice age on Mars and the present ice age on Earth. It was suggested that the synchronism of those events required a change in the solar luminosity. Very few geologists now believe that the Martian rivers are young enough to be related to recent terrestrial geologic history. It remains for future exploration of Mars to find any evidence of solar luminosity variation on Mars on time scales of less than 10^9 years. Of course, there is strong evidence in banded sedimentary deposits at the Martian poles of climate change on a time scale of 10^5 years which is related to perturbations in the Martian orbit, just as the glacial ages on the Earth may be related to variations in the terrestrial orbit.

It is well known that the Earth's upper atmosphere responds to variations in the sun's ultraviolet luminosity and in the high energy particle flux which occur over the solar cycle. Photochemical and particle processes also occur in planetary atmospheres and much work could be done in searching for solar cycle variability on the planets. An interesting example of a possible relationship is the observed secular brightness variations of Titan, Neptune, and Uranus. These brightness variations do not seem to represent simple variations in the solar luminosity. A study of Titan suggests instead a correlation between Titan's cloud albedo and the solar cycle. The clouds of Titan, which are probably produced photochemically, seem to change their particle size and optical depths by small amounts over the solar cycle. If these observations are confirmed by futher study they may represent the largest response to the solar cycle yet found anywhere in the solar system.

NATURE OF THE FOSSIL EVIDENCE: MOON, METEORITES, AND PLANETS.

Robert M. Walker, Physics Department and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

On previous occasions where solar scientists have confronted those in the planetary community who study the past history of the sun, it has been my experience that the former are sometimes left unsatisfied. Responses by planetary scientists to legitimate questions probing the quantitative level at which various solar properties have been established and the precise times to which those determinations refer, are sometimes complicated. The problem lies in the nature of the evidence; it is fragmentary, covers a wide range of physical effects, and is derived from very different kinds of objects. My goal here is to describe in qualitative terms some of these boundary conditions to those not working in the fields of meteorites and lunar samples. The quantitative aspects will be treated in succeeding sessions of this conference.

Consider first the diversity of objects that comprise the lunar sample collection. Conceptually the simplest possible sample is an igneous rock derived from an ancient lava flow that has been shielded from radiation by overlying material since it cooled. An impact burrows down to the bed rock layer and excavates a sample, throwing it out on the lunar surface where it lies undisturbed until collected by an astronaut. The rock is exposed to solar wind, solar flares, and galactic cosmic rays preserving a record of their properties in the form of implanted ions, radiation damage effects both structural and electronic, radionuclides ($E_p \geq 10$ Mev), stable cosmogenic nuclides, and fossil heavy ($Z \geq 20$) nuclei tracks. Typical penetration distances range from $\sim 5 \times 10^{-6}$cm for solar wind effects, mms to cms for solar flare effects, and cms to meters for galactic cosmic ray effects. Some of the effects, eg: radionuclides, have a built in time constant and give differential measurements; others, eg: tracks, give integral results. In principle, therefore, the sudy of a variety of effects as a function of depth can be used to infer the properties of energetic particles at 1 AU for the length of time that the hypothetical igneous rock fragment has lain undisturbed on the surface.

Such simply irradiated samples are rare, and strictly speaking, do not exist. Most rocks have complicated irradiation histories indicating that they have been partially reburied re-excavated, etc. The simplest illustration of this fact is to note that many lunar rocks have impact pits on <u>all</u> sides. All rocks have also suffered from erosion to a lesser or greater degree due (at least in part) to micrometeorite bombardment.

Nonetheless reasonable approximations to the ideally simple situation do exist. Rocks from the South Ray Crater at Apollo 16, for example, were excavated two m.y. ago and have been modified relatively little since then. Rock 12054 was covered by glass relatively recently and has been the object of intense, correlated study by a number of investigators. Crystals exposed at the bottom of vugs (gas bubble holes in rocks) are partially protected and give directional information. I could multiply the examples manyfold; the message should be clear, not all crystalline lunar rocks are equally interesting for studying the energetic particle record of the solar system. Special rocks and special parts of rocks must be located and studied.

If dynamic lunar processes limit the number of simply irradiated rocks, as well as the time scale over which variations can be studied ($\lesssim$ 50 m.y. and typically $\lesssim$ 5 m.y.), they create other opportunities for studying solar variations - perhaps dating back to the early solar system. By no means are all lunar rocks crystalline. Many are breccias that consist of a jumble of fragments that have been sintered together as a result of impacts. Some of these have been derived from deep depth where the individual fragments never were subjected to radiation prior to the breccia being exposed on the surface. Such rocks serve much as crystalline rocks in studying radiation effects. But there is a more interesting class of breccias that consist of crystals and fragments that were once part of the lunar surface where they were individually exposed to the sun as the surface was stirred by bombardment with interplanetary debris. Such rocks contain large quantities of solar wind type rare gases; individual crystals removed from the interior of such rocks bear witness to their surface exposure in the form of solar flare tracks (distinguishable from tracks produced by galactic cosmic rays by virtue of their large numbers and their characteristic rapid attenuation as a function of depth) and the presence of microcraters. Breccias of this type preserve the record of prior exposure to varying degrees depending on the violence of the event that produced them.

One of the key questions that needs still to be answered for most "solar breccias" is the time at which they were assembled. We know that they give snapshots of the sun at different times in the past but we do not know, in general, when that time was. Nonetheless there is good evidence, some of which you will hear at this conference, that some of the breccias are very old and that the solar properties that they record refer to an early epoch of the solar system. In our own laboratory we have shown that solar breccias found in highland (old) regions contain distinctive xenon isotopes produced by the decay of the presently extinct isotopes ^{129}I ($T_{\frac{1}{2}} \sim 17$ m.y.) and ^{244}Pu ($T_{\frac{1}{2}} \sim 80$ m.y.). Such effects are not found in mare breccias. The gas was not produced by <u>in situ</u> decay but was probably added as a solar-wind related re-implanted component at a time when distinct xenon reservoirs existed that were rich in gas produced by the decay ^{129}I and ^{244}Pu. Although we do not know the precise time at which the gas was added, it is reasonable to assume that solar breccias with large extinct isotope components were formed at an earlier time then those that do not contain these effects.

One of the stiffest challenges to lunar scientists is to read the solar record that we <u>know</u> is recorded in lunar soil samples, particularly samples from deep drill cores that were obtained by the astronauts on the later Apollo missions. With rare exceptions, most samples of lunar soil contain a large percentage of crystals and fragments that have been exposed directly in free space to the sun. This can be demonstrated in a variety of ways, perhaps the simplest being the observation of tiny microcraters ($\gtrsim 1000$Å) on the surfaces of individual grains. Three interrelated problems exist in interpreting the record. It is first necessary to make measurements that refer to a specific solar property. This can be done statistically by taking a bulk sample and measuring, for example, the composition of solar wind rare gases. Or it can be done on an individual grain by grain basis measuring, for example, the thicknesses of radiation damage layers produced by solar wind bombardment (examples of both types of measurements will be presented at this conference). In the latter type of measurement it is also important to know the length of time, at least on the average, that a grain was exposed on the surface. Finally, it is obviously desirable to specify when the bombardment took place.

Although certain investigators have treated lunar cores as if they were sea sediment cores with a steady progression in time from top to bottom, the true situation is much more complicated. The stochastic nature of the stirring process (this subject is treated explicitly in the talk by Arnold) limits the extent to which a specific core layer can be associated with a specific time in the past. However, while complicated, the situation is not hopeless. For example if a core has lain largely undisturbed for a long time, it will show a characteristic depth distribution of isotope effects due to neutron capture. The nuclear cascade produced by galactic cosmic rays first gives an increase in the neutron flux with depth reaching a maximum and then falling off at deeper depths. This neutron profile was directly measured in an experiment flown to the moon on the Apollo 17 mission. Using isotope measurements it is possible in some cases to be certain that the solar bombardment being studied took place at $\geq 10^9$ yrs ago. As you will see during this conference, progress is also being made in relating rare gas patterns to a time sequence of bombardment.

Meteorites offer a complementary way to study solar history. In direct analogy with lunar "solar breccias," certain meteorites contain crystals that were once exposed to the sun, probably on the surfaces of small parent bodies. As in the lunar case, one of the key problems is to establish when the solar irradiation took place. Because of the measured antiquity of crystalline fragments from most meteorites (4.6×10^9 yrs), it has frequently been assumed that the irradiation took place very early in the history of the solar system. However recent measurements give compaction ages (breccia formation) of no greater than 4.3×10^9 yrs; the measurements can also be interpreted as being consistent with an even more recent compaction age and the antiquity of the solar record is thus uncertain. One of the advantages of the meteoritic breccias is that it appears that individual crystals have had somewhat simpler irradiation histories than is the case with lunar crystals. Interesting differences have also been found between various meteorites; studies of the solar record in these objects should continue to be an active field of research. Another problem with the meteorite record is the unknown origin of these objects. It is generally assumed that the solar effects were recorded at a distance from the sun corresponding to the location of the main asteroid belt, but this is not yet proven. Meteorites can also be used to study solar effects indirectly by measuring the constancy of galactic cosmic rays over periods of time from 10^5 to $\lesssim 10^9$ yrs.

The planetary record may some day prove to be the most decisive indicator of solar changes. Proven simultaneity of climate changes on different planets (or their satellites) would bear clear witness to a variable sun. Our current state of knowledge is enough to suggest fascinating possibilities for future research while remaining sufficiently incomplete so as to make definitive conclusions unlikely in the near future. Defining the past history of the sun will continue to be an important motivation for future planetary exploration.

To return to my initial theme, I hope it will be obvious to our solar physics colleagues that the planetary community, while seeing the past record through a glass darkly, has many intriguing objects with which to work and is making steady progress in an area of research that did not even exist a scant decade ago. Important constraints on solar variability have already been established and some major mysteries, such as the apparent temporal variation of the $^{14}N/^{15}N$ ratio in the solar wind, have emerged. Continued development of the understanding of lunar, meteoritic, and planetary materials as well as the development of new experimental approaches should lead to a further delineation of the solar record.

THE NATURE OF SOLAR BEHAVIOR. N. O. Weiss, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, England.

The aim of this review is to summarize our knowledge of the present state of the sun and of its evolution since its formation as a main sequence star. In particular, it is necessary to indicate what limits can be set to solar activity during the history of the sun. This condensed account will provide an astrophysical background to the more detailed papers to be presented later in the conference.

Although only the suface of the sun can be observed, there are enough theoretical models to provide a fairly reliable description of the interior structure of the sun. Energy is generated (by the p-p reaction) near the center, at temperatures around 10^7K, and carried outwards by radiation for most of the solar radius. In the outer 30% by radius (only 1% by mass) convection takes over and this convective zone is responsible for solar activity. Models of the present sun and of its evolution from the main sequence seem reliable enough, despite worries over the neutrino problem.

The sun may conceal a primordial field in its interior but the observed magnetic fields alter with the solar cycle, whose period fluctuates around 22 years. Magnetic flux emerges through the surface in active regions, within which sunspots occur, and these active regions show systematic changes in latitude and polarity which define the cycle. This oscillating behavior is produced by a hydromagnetic dynamo driven by turbulent motion in the convective zone. The theory of homogenous dynamos is difficult but many models have been put forward and the basic features of the cycle are now understood.

The dynamo oscillates irregularly: in the seventeenth century there were hardly any sunspots, though the sun was much more active in early medieval times than it is now. Such excursions are typical of the solar cycle in the last few thousand years and, presumably, over most of its history. To discover the possible range of activity we must turn to other stars. Other main sequence G stars do show evidence of activity, often much stronger than in the sun. Comparison with similar stars in the Hyades and Pleiades shows that magnetic activity declines as stars grow older. In fact, recent observations indicate that the present sun is relatively feeble compared with other active stars.

SOLAR FLARE TRACKS, THERMOLUMINESCENCE AND SOLAR WIND IMPLANTED PARTICLES IN LUNAR ROCKS. Ernst Zinner, Physics Department and McDonnell Center for the Space Sciences, Washington University, St. Louis, Mo. 63130

The bombardment of lunar surface samples by solar particles leaves a large number of effects. Comparison of effects of different origin accumulated over the exposure time of individual samples can in principle be used to determine solar particle fluxes over different time periods and to measure their possible changes. This review will concentrate on the record of solar flare tracks, thermoluminescence and solar wind implanted particles in lunar rock samples. Complementary reviews of solar particle effects accumulated over the same time period are given by Hartung and Fireman.

The review by Crozaz discusses the formation of tracks by solar flare and galactic heavy nuclear particles. Thermoluminescence (TL) is produced in lunar crystalline material by solar flare and galactic cosmic ray particles, mostly protons(1). Upon heating release of the stored TL leads to the emission of light whose amount is proportional to the total radiation dose received by the sample. By comparison with the TL produced by irradiation with a known laboratory source the total natural dose can be measured. The TL in lunar rocks falls off with depth reflecting the energy spectrum of solar flare and galactic protons. The solar flare TL extends to a depth of $\sim$1cm. Solar wind ions are implanted into lunar materials on a depth scale of about 300Å(2). Different elements are measured by different techniques. Only a few measurements have been made on recently exposed rocks. The one discussed here is that of Mg and Fe in a plagioclase crystal made by ion microprobe(3).

The erosion of lunar rock surfaces by solar wind sputtering and micrometeoroid impacts sets limits on the times over which different particle effects can be accumulated depending on the depth scale of these effects. For solar wind implantation the record extends over $\sim 10^4$ years, for solar flare tracks over $\sim 10^6$ years. Because of thermal draining on the moon the TL record of lunar rocks extends over $\sim 5 \times 10^3$ years. The ability to measure any of these effects depends very much on the availability of lunar rocks which have been exposed over short time periods. The number of reliable measurements is limited by the small number of such samples. Furthermore, the condition of lunar rock surfaces which are far from being perfect detectors gives rise to uncertainties in any of these measurements. A factor of two seems to be the typical uncertainty within which different particle fluxes can be measured.

If one wishes to determine the possible change of the rate of any process taking place on the lunar surface, there are three ways in which this can be done for the particle fluxes we are concerned with. 1. The accumulated effects of two independent processes are compared in different samples exposed for different times. 2. The rates of one process measured over different time periods are compared. 3. The accumulated effects of two processes whose rates have been measured over different time periods are compared in an individual sample exposed for a certain time. Whereas the last two methods require the measurement of an absolute rate by using an exposure time clock, the first method does not require this. Examples of each kind are given:

1. Comparison of solar flare tracks and microcrater densities. Morrison and Zinner(4,5) and Hutcheon(6) have measured microcrater densities on lunar rocks and track densities in crystals below the same surfaces. A wide range of exposure times could be covered by selecting either surfaces exposed for a short time or surfaces which hadbeen exposed through a small solid angle protecting the crystals from erosion. Morrison and Zinner(5) obtained the same ratio of crater to track densities in three rock samples whose exposure time differs by a factor of $\sim$35 (Fig. 1). Thus no relative change of these

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two rates is indicated. If one accepts the arguments presented by Zook et al. (7) for a constancy of the cratering rate the conclusion would be that the solar flare track production rate remained constant. Hutcheon(6) obtained a much higher track/crater density ratio. However, the possibility of laboratory differences in track measurement(8) and shielding by a thin dust cover(9) could explain this discrepancy. Track density gradients are almost the same in all these measurements indicating constancy of the energy spectrum of heavy solar flare particles.

2. Comparison of solar flare particle rates measured over different periods. The measurement of a rate necessitates the use of a clock. The clock for the measurement of the track production rate in lunar rocks is provided by galactic cosmic ray effects. Galactic cosmic ray tracks were used in the measurements by Hutcheon et al.(10) and Yuhas(11), whereas Blanford(12) measured solar flare tracks in a rock with a known Kr-Kr exposure age. While there is a considerable disagreement between Hutcheon et al.'s production rate and the other values(9) (see however (8)), later measurements(5,13) agree with the Blanford value. From this one concludes that the track production rate is known within at least a factor of two. This rate which has been measured as an average over a time of 2×10^6 years could be compared with that obtained from the Surveyor glass which has been exposed for 2.6 years(14-16). Because of the known variation of the intensities and energy spectra of individual flares, this time is too short to make conclusions about the long term behavior of solar flare particles. The rate of TL production over the last 5×10^3 years (1), however, agrees well with the track production rate. In case of TL measurements the clock is provided by the thermal draining under lunar conditions. Comparison of TL effects caused by protons and tracks produced by Fe particles assumes a time constant chemical composition of solar flare particles for which there seems to be good evidence (see review by Crozaz). Both TL(1) and track measurements(11) have been compared with solar flare proton fluxes derived from the production of radionuclides (see reviews by Fireman and Reedy) averaging over time spans from a few years to $\sim 10^6$ years, as well as with contemporary satellite measurements(11) over the last two solar cycles. Again there is essential agreement except for the ^{14}C values (see, however, Fireman's review about solar flare produced ^{14}C). Measurements of solar flare production rates thus do not indicate any changes over the last 10^6 years.

3. Comparison of the solar flare track production rate with the solar wind flux and the microcratering rate. Solar flare tracks accumulated in an exposed lunar sample can be used to measure its exposure time on the moon. Likewise, the accumulated effects of any other independent process provide a second exposure time. Generally, the rates of these two processes are measured by averaging over different time periods which, in turn, are different from the exposure time of the sample under study. If the rates in question are constant in time, the independent exposure times should agree. Disagreement could, among other things, be caused by a time variation of the solar flare activity or of the process it is compared with(17). The solar flare activity is not directly correlated with the solar wind flux which thus can be viewed as an independent process. Zinner et al.(3) derived a solar wind exposure age of a lunar sample exposed for 1.6×10^4 years(12) from the measurement of surface enhanced Mg and Fe considered to be implanted by the solar wind. The solar wind flux was obtained from present day measurements(18,19). There is good agreement between the solar flare and the solar wind exposure age. Another possibility is to compare solar flare ages with ages obtained from crater densities(17). There is a number of rock samples for which that can be done using either craters of 1μm diameter or smaller or craters >10μm.

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The best sample is rock 12054, because craters could be measured from <0.1μm up to 1mm in size(5). If small (<1μm) craters are used together with satellite measurements of the interplanetary dust flux in the corresponding mass range (20,21), the cratering exposure age agrees well with the track age(5). On the other hand, if the Lunar Orbiter penetration data(22) are used to derive a cratering rate for large craters the cratering age is substantially smaller than the track age(17). There is no satisfactory explanation for this disagreement but a resolution must wait for better measurements of the contemporary meteoroid flux.

In conclusion, there exists no compelling evidence from the record in lunar rocks that the solar flare activity underwent any changes in the last 10^6 years.

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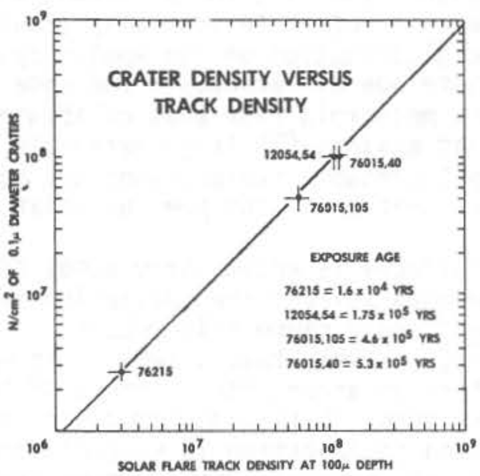

Fig. 1 The density of microcraters of 0.1μm or larger diameter is plotted against the solar flare track density measured at 100μm below the sample surface. Four samples with different exposure ages (calculated from track densities (12)) are compared.

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Lunar rock data exists that can be interpreted to show that large variations in solar flare activity occurred during the past 10^4 to 10^5 years. Other interpretations of the same data may be made, however, that do not include the hypothesis of variable solar flare activity. In addition, there are other, independent, lunar data that may be interpreted to indicate that solar flare activity has not varied during this period. It is my purpose here to re-examine these data and interpretations.

a. The solar flare track-within-pit data of Hartung and Storzer (1) showed that the spatial densities of tracks (thought to be solar flare Fe tracks) within the glass linings of meteoroid impact pits varied in a non-linear way with the cumulative number of pits examined. Zook et al. (2) later interpreted these data to suggest that the production rate of solar flare Fe particles varied in time with a large increase between ten and twenty thousand years ago. An alternative explanation that the meteoroid impact pit production rate may have varied with time was not favored (2) but was not proved completely invalid. A complicating factor arose from research by Comstock and Hartung (3) that suggested that the tracks observed by (1) were not due to Fe ions (but were, perhaps, due to heavier ions). More important, perhaps, is the accumulating evidence that obscuration by loosely bound dust is a very important factor in influencing the various rates of processes occurring on or near lunar rock surfaces. The evidence is largely detailed in (4), (5), and (6). It is shown in (4) that loosely bound dust is almost certainly the agent for producing a nonlinear distribution of submicron impact pits and accreta within larger impact pits. Thus we see that there are at least three viable alternate explanations for the Hartung and Storzer data. The variable solar activity explanation is only one possibility. Dust obscuration is a strong candidate for an explanation but has not been proved to be the correct explanation. The depth of dust obscuration remains somewhat uncertain.

b. Lunar rock surface exposure ages deduced from solar flare track measurements are typically about six times greater than the surface exposure ages deduced from impact pit counts (7). Shielding by loosely bound dust that could prevent the creation of 20 μm in diameter and larger pits does not appear to be severe enough to cause the observed difference. That is, the preferential suppression of the smaller pits by dust does not appear to be nearly great enough in comparison to the impact pit size distribution on the Apollo spacecraft windows (15) to account for the exposure age differences. The same window data also establishes the present-day meteoroid flux that calibrates the "impact crater exposure age." We have argued against (2) large meteoroid flux changes in time. Thus the two remaining most probable explanations are solar flare variability or a grossly incorrect calibration of the present solar flare track production rate.

c. The ^{14}C activity near lunar rock surfaces is about three times too high (8), (9) to be understood under present-day solar flare spallation rates. An increased solar flare activity in the past could cause this result. Begemann et al. (8) and Fireman (10) suggest, however, that direct solar wind implanted ^{14}C is the likely explanation. Fireman argues that because of the observed thermal release pattern and because more ^{14}C is associated with the finer grained fraction of the soil, solar wind implantation is strongly implicated. The latter argument is not a unique one, however. It is known that the finest-grained soil is right at the surface of a meteoroid reworking zone. Thus it is very probable that solar flare produced spallation ^{14}C would also be in the finest grained soil component. These lunar soil size fractions should be checked for other solar flare spallation products such as ^{26}Al.

d. ^{59}Ni measurements by Lanzerotti et al. (11), on lunar rock 12002 gave a result about a factor of two too high near the rock surface using the present estimated production rate of ^{59}Ni. They suggested that, because of uncertainties in the data and in the ratio of alpha particles to protons in solar flares, their result was consistent with a constant solar flare activity. However their result, as well as the results summarized in a, b, and c, were also consistent with a large positive excursion of solar flare activity 10,000 to 30,000 years ago.

e. The only evidence besides the solar wind ^{14}C evidence against solar variability in the past 10^4 to 10^5 year time frame is that presented by Morrison and Zinner. They note that the ratio of the spatial surface density of 0.1 μm diameter (and larger) meteoroid impact pits to the solar flare track density at a depth of 100 μm does not change for three lunar rocks of different exposure ages. Although these data are of considerable interest, the author's conclusions are not firmly based because: (a) the 0.1 μm diameter pit density is known to vary from place to place on a single rock (6), (13); (b) solar flare particles and beta meteoroids (which cause the 0.1 μm diameter pits) are both known to be directional--but probably not with the same solid angle distribution. Therefore comparing a ratio in a crevice--as for 76015--with a well exposed surface--as for 12054 and 76215--is risky at best; (c) the slopes of the solar flare track profiles for each of these rocks is rather flat. Comstock (14) would suggest that only the steepest solar flare track profiles have not been affected by shielding due to dust or affected by erosion.

In summary, it is concluded that definitive evidence on the variability or nonvariability of solar flare activity in the time frame of 10^4 to 10^5 years does not yet exist. The strongest evidence that solar variations have occurred is probably that given in b. and the strongest counter evidence is that given in c. and e. The counter evidence has two qualifications: (a) It does not rest on data from which unique and firm constraints on solar variability may be drawn and (b) a variety of variable solar flare activity scenarios can be imagined which would satisfy conceivably valid constraints c. and e. but also satisfy the other data. Thus I conclude that there is at least a hint that a dramatic increase in solar flare activity may have occurred 10 to 30 thousand years ago. Further lunar and terrestrial research covering this time interval should therefore be greatly encouraged.

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SAMPLE NUMBER INDEX*

HEAVENLY BODIES INDEX*

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